

**Summary of Preliminary Groundwater Flow  
and Contaminant Transport Simulations  
for Motorola/Honeywell  
OU2 System  
Phoenix, Arizona**

**Version 3.1  
March, 2001**

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**For:  
U.S. Environmental Protection Agency Region IX  
Under Interagency Agreement DW96955414-01-0**

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## **1.0 INTRODUCTION**

### **1.1 THE PROBLEM**

The Motorola 52<sup>nd</sup> Street Superfund Site located in Phoenix, Arizona, encompasses an area of groundwater contamination in the central and eastern part of the city north of Sky Harbor Airport. One major source of contamination is the Motorola 52<sup>nd</sup> Street manufacturing facility where trichloroethylene (TCE) was found at high concentrations in the aquifer beneath the facility. A plume of TCE extends westward in the aquifer from the Motorola facility.

To the southwest of the Motorola facility is a Honeywell (formerly Allied Signal) manufacturing facility that also has associated TCE contamination in the aquifer.

Both Honeywell and Motorola hired different teams of consultants to advise them about the fate and movement of TCE in the aquifer. Both teams have created models of the groundwater flow system. The teams differ in their interpretation of how the contaminants move at the site.

The Honeywell team contends that a bedrock ridge running NW-SE across the facility site is permeable because of “lows” or “saddles” across the ridge. This allows groundwater flow to move across the ridge (NE to SW) under the facility site and bring contaminants from Motorola’s plume with it.

Motorola claims that the ridge is impermeable and that it acts as a barrier to groundwater flow. Both groundwater flow and contaminants from Motorola’s plume, plus releases from the Honeywell site north of the ridge, are then deflected around the ridge and move in a westerly direction along Van Buren Street. The contaminants will then be captured by the OU2 treatment system.

Test drilling along the ridge north of the facility has defined the ridge in more detail but there is still disagreement between the two groups on the nature of the ridge and the values of various aquifer parameters to be used in calculating groundwater flow and plume movement.

In 1992 Motorola installed a system of recovery wells west of the 52<sup>nd</sup> Street facility between 44<sup>th</sup> and 48<sup>th</sup> Streets; this recovery system is designated Operable Unit 1 (OU1). An additional system of recovery wells, Operable Unit 2 (OU2), is designed for a location northwest of the Honeywell Facility. OU2 is intended to create a capture zone across the entire width and depth of the contaminant plume in the vicinity of Interstate 10.

### **1.2 THE PURPOSE**

The Hydrodynamics Group was hired on behalf of the U.S. Environmental Protection Agency (EPA) to provide an independent evaluation of groundwater flow and contaminant transport in the vicinity of both facilities, to comment on the effectiveness of the OU2 treatment system, and to give an opinion on the possibility of contaminants moving past OU2, both before and after it becomes operable.

This report is the result of The Hydrodynamics Group’s investigation of the groundwater system that included the creation of a preliminary model of the site. This preliminary model was intentionally simplified to a single layer to provide a stable, flexible, and cost effective means of evaluating the effects of changing aquifer characteristics, including hydraulic conductivity, porosity, and bedrock ridge configuration, on the predicted contaminant distribution. The preliminary model was not intended to exactly match the data from

each observation well, rather the objective was to obtain a coherent view of how contaminants may have moved in the aquifer and to direct future data gathering and modeling efforts. The extent of The Hydrodynamics model study area is shown in Figure 1.1. The specific objectives of the modeling effort were as follows:

1. Analyze the effects of the bedrock ridge on contaminant flow;
2. Determine the sensitivity of the model to various parameters;
3. Evaluate the effectiveness of the OU2 treatment system;
4. Estimate the relative contribution of each party to the contaminant plumes; and
5. Direct future data gathering and modeling efforts.

The following sections present a discussion of the Hydrodynamics Group modeling effort. Previous modeling efforts are also discussed. Conclusions relative to the report objectives are also presented.

## 2.0 LITERATURE REVIEW

### 2.1 HYDROGEOLOGY

Lithologic and stratigraphic data, aquifer properties, groundwater elevations and VOC concentrations have been compiled from borings, well installations, and rock cores. These data come from numerous reports by Dames and Moore (1987, 1992, and 1993), Conestoga-Rovers (1997), and Honeywell (1999a, and 1999b). The site description that follows is an overview of the geology; it is offered as background to understanding the hydrogeology of the area.

The area of investigation is located in the eastern part of the western portion of the Salt River Valley Basin. Crystalline rocks that range in age from Precambrian to late Tertiary form the oldest rocks beneath alluvial valley fill deposits. The crystalline rocks consist of igneous and metamorphic rocks. Granites, schist, gneiss, metavolcanics, and quartzite crop out in the hills and mountains in the area. The buried bedrock consists of similar lithology.

Tertiary sedimentary rocks that grade from moderately to well cemented overlie the crystalline rocks; these include the Camel's Head Formation and the Tempe Formation. The Camel's Head Formation underlies the Tempe Formation and is a well lithified alluvial deposit consisting of coarse, angular rock fragments in a fine-grained matrix. The Tempe Formation overlies the Camel's Head and consists of moderately lithified shale and siltstone with some sand and gravel. Throughout the region there are extrusive volcanic rocks of early to middle Tertiary age; these are composed of rhyolite and basalt. There are also more recent Quaternary age basalt flows.

The basin-fill deposits overlie the Tertiary rocks and are Quaternary in age. The Quaternary deposits are composed of unconsolidated clastic sediments derived by erosion of the surrounding mountains. The local bedrock is the source of material for the alluvium.

The ground surface at the Motorola facility is 1220 feet elevation; the land surface slopes gradually toward the Papago Freeway where the ground surface is about 1100 feet elevation. Figure 2.1 is a topographic contour map of the study area.

The bedrock in the area is composed of the crystalline rocks and the Tertiary sediments. The topography of the buried bedrock is a somewhat undulating surface dipping westward away from the Papago Buttes near the Motorola 52<sup>nd</sup> Street facility. A regional bedrock surface map shows the bedrock dropping from about 1180 feet elevation at the eastern edge of the Motorola 52<sup>nd</sup> Street facility to about 900 feet elevation at Papago Freeway 4 miles to the west. In between these two points are two bedrock "ridges": 1) a small ridge just west of the Motorola facility, and 2) a larger one that underlies the Honeywell facility. The top of the Motorola bedrock ridge is at about 1160 feet elevation and the top of the Honeywell bedrock ridge is about 1060 feet elevation. Between the ridges there is a bedrock "valley" with its bottom at an elevation of slightly less than 900 feet.

The alluvial valley-fill deposits are typical for arid southwestern deserts basins. The thickness of the alluvium ranges from absent on the highlands at the basin margins to over 10,000 feet thick at the center of the basin. At the Motorola Superfund site, the alluvium ranges from very thin (~50 ft) around the Papago Buttes on the eastern edge of the site to approximately 250 to 300 feet thick north and west of the Honeywell facility near the Papago Freeway. At the Honeywell facility, the alluvium is thin over the bedrock ridge. There is disagreement between Motorola and Honeywell over the nature of the bedrock ridge, which is an area of continuing investigation. The alluvium consists of conglomerate, gravel, sand, silt, clay, and

evaporites. It is made up of sequences of coalesced alluvial fan, playa, and fluvial deposits. The alluvium becomes finer toward the center of the basin.

The Salt River Valley basin alluvial deposits make up three loosely defined units. In ascending order they are: the Lower, Middle, and Upper Alluvial Units. The Lower Alluvial Unit (LAU), in the deeper part of the basin, consists of conglomerate and gravel; the Middle Alluvial Unit (MAU) consists of predominantly silt and clay, and the Upper Alluvial Unit (UAU) consists of mainly gravel and sand (Corkhill, et al, 1993). The UAU is the only unit present at the OU2 site. OU2 is near the basin margin where the LAU and MAU are not present. Although there are undoubtedly different lithologic units within the UAU there are insufficient boreholes and wells to define them, consequently, the UAU is generally treated as one lithologic unit—a single aquifer.

The bedrock consist of unweathered crystalline and well-cemented sedimentary rocks that are both weathered and unweathered. In most places the bedrock is not very permeable; it forms a lower boundary for the aquifer. Locally, the bedrock may be more permeable due to fractures and weathering near the contact with overlying sediments. Slug tests at EW-19D and EW-22D (Figure 2.2) in the upper bedrock yielded hydraulic conductivity values of 5.6 and 9.8 ft/day respectively; these values represent the weathered bedrock. Hydraulic conductivity values in the unweathered bedrock range from 0.005 to 0.05 ft/day.

The saturated unconsolidated alluvium overlying the bedrock is two to three orders of magnitude more permeable than the bedrock. Analysis of the results of the DM 518 (Figure 2.2) aquifer test yielded a hydraulic conductivity value of 200 ft/day (Dames and Moore, 1993). Analysis of the TEW-1 (Figure 2.2) aquifer test data yielded a hydraulic conductivity value of approximately 450 ft/day (Conestoga-Rovers, 1997). Most of the pumping tests and slug tests have fluctuations in water level caused by other pumping in the valley; these fluctuations make the tests difficult to interpret. The test analyses of hydraulic conductivity produce values that can vary by +/- 50 percent.

Laboratory tests of undisturbed samples and cores were used to determine both porosity and specific yield. These data and the above mentioned aquifer tests were used to determine material properties. Porosity of the alluvium ranges from 20% to 30%. The unweathered crystalline bedrock has a porosity of approximately 1% and the weathered bedrock a porosity of approximately 20%.

Data from the Arizona Department of Environmental Quality (ADEQ), Arizona Department of Water Resources (ADWR), Salt River Project (SRP), monitoring wells from landfills, and the Motorola's water level data base for 4<sup>th</sup> quarter 1996 were used to make a water level map of the model domain.

## **2.2 CONTAMINANT SOURCES**

EPA and ADEQ conducted a Potentially Responsible Parties (PRP's) search at OU1 and in 1992 completed a supplemental search for OU2. ADEQ and EPA have concluded, after several years of investigation, that Motorola's 52<sup>nd</sup> Street facility and Honeywell's facility at 111 South 34<sup>th</sup> Street are two significant sources of groundwater contamination. The existence of additional sources from the numerous current and historic industrial facilities in this area is possible, as suggested by the TCE contour map shown in Figure 3.2. EPA is currently in the process of identifying additional PRP's. Should significant additional sources be identified, they can be added to the transport model and their contributions to the contaminant plume can be evaluated, both to assist in determining the effectiveness of the OU2 interim remedy and to further the Remedial Investigation for OU3.



## **3.0 DATA COLLECTION AND COMPILATION**

### **3.1 SOURCES AND QUALITY OF DATA**

Geologic and hydrologic data were collected from a number of sources, including ADEQ, ADWR, SRP, the U.S. Geological Survey (USGS), and reports prepared by consultants for Motorola and Honeywell. Data were collected and assembled into a database and integrated with a Geographic Information System (GIS) by SAIC.

Laboratory tests of undisturbed samples and cores were used to determine porosity and specific yield. These data along with the above mentioned aquifer tests were used to determine material properties and their distribution.

### **3.2 ANALYSIS OF DATA**

As part of our analysis we assembled data to describe both the water table and the distribution of the contaminants. This information is critical to our model analysis. We expect the model to reproduce these sets of information. Tops and bottoms of aquifers were taken from borehole and water well lithologic logs. Well locations were verified from the well records, Township/Range coordinates were converted to State Plane coordinates and the locations were then plotted on maps. Ground elevations were taken from the well records or estimated from digital terrain maps. Elevations for tops and bottoms were then calculated, plotted and contoured using SURFER® or manually by a professional geologist.

#### **3.2.1 Water Table**

Water level elevations were sorted into years and quarters and then plotted on maps. Records from bedrock wells and overburden wells were separated but there were not enough records to create a contour map of water levels in the bedrock. We contoured all of the available data for 1996 to create a water table map—Figure 3.1. We chose 1996 because the data are more complete. The data are sparse to the north and northwest. We made no attempt to filter the data. There are what appear to be anomalies; one of these is a small closed contour to the northeast of the Honeywell facility. There is also a closed low just to the west of the Motorola facility that is the effect of the OU1 pumping.

#### **3.2.2 TCE**

Figure 3.2 is a contour map of the TCE distribution in the 4<sup>th</sup> Quarter, 1996. There are several distinct hot spots or "pods" of contamination. The map shows the isolated pods of TCE that extend to the west along Van Buren and Washington Streets. These pods are centered on "high" values but the exact extent of these pods cannot be determined from the existing data set. There are enough data points to show lower values between the "high" values. This indicates that the high values do not cover a large area. However, the data points were not sorted by depth and so it is possible that the "highs" and "lows" are associated with different Lithologic units. The hydrostratigraphy requires more detailed evaluation and probably more data points. At approximately the 50 micro-grams/liter contour and above the plume can be considered more or less continuous; within this contour there are no lower values. The nature of groundwater flow and contaminant movement does not produce pods of contaminant unless there are additional sources, or there are large pulses of contaminant from a single source. The final plume was hand-contoured, taking into consideration the source locations, groundwater table elevations and estimated flowlines but the 3-D nature of flow was not evaluated.

### **3.2.3 1,2 DCE**

Figure 3.3 is a map of the 1,2 DCE distribution in 1996. It also shows several pods of DCE distributed in a similar pattern to the TCE. 1,2 DCE is thought to be a degradation product of TCE.

### **3.2.4 Vinyl Chloride**

Figure 3.4 is a map of the vinyl chloride distribution in 1996. Again there are pods of vinyl chloride. The concentrations are much lower than either the TCE or the DCE. Vinyl chloride is a degradation product of DCE.

## **3.3 DISCHARGE AND RECHARGE CONDITIONS**

The several models of the area use constant head flow boundaries to model groundwater flow from east to west. The Salt River is outside the boundaries of most of the models, except the regional model. Water appears in the Salt River only intermittently; flow in the Salt River influences groundwater flow seasonally in the area of the airport. The Grand Canal cuts the study area from southeast to northwest; it was unlined before 1986. We did not explicitly investigate the impact of the Grand Canal on the TCE plume from Motorola; the influence of the Grand Canal could be investigated with the model in the future. This would require at least two time steps per year over a twenty-year time period.

Recharge from rainfall is small and has been averaged over the model domain in all the models. Pumping from irrigation wells in the northwest quadrant of the study area is not well documented and may require further evaluation. This pumping should not have a major impact on the plume because of the distance between the two. The influence of the pumping is reflected in the initial water table contours.

## **3.4 HYDROGEOLOGIC DATA**

The aquifer parameters and regional hydrogeology have already been discussed. Specific-capacity data available from municipal and irrigation wells were analyzed to obtain transmissivity and hydraulic conductivity values. These measurements are only estimates of transmissivity and hydraulic conductivity, but they provide information on trends over the study area. Contour maps for these values are shown in Figures 5.3 and 5.4. Testing of the new wells at OU2 could give better values for hydraulic conductivity. The models would then be updated with these values.

## 4.0 GROUNDWATER MODELS

The interaction of the hydrologic cycle on groundwater is complex, with numerous feedback loops within the system. One of the principal tools of the hydrologist is the use of structure imitating, numerical computer models for analysis. How good or bad the models are depends upon the creativity of the modeler, and how well the models capture reality.

Models by their nature are abstractions of reality. They are constructed to reflect reality for the purpose of analyzing a natural system. Often one wants to predict the behavior of the systems under conditions differing from those that exist in the real system; or one wants to examine cause and effect with respect to the real system.

In creating models there is a tension between simplicity and complexity. The tendency on the part of the modeler is to build into the model everything one knows about the real system. This often leads to complex models. Models have become more complex as digital computers have grown increasingly powerful. As the models increase in complexity they become difficult to calibrate against empirical data—the relevant empirical data is either extremely sparse or non-existent. As the models increase in complexity it is often difficult to see clearly cause and effect. As the model become increasingly complex it becomes more difficult to solve the problem numerically; often the models become computationally unstable.

It is questionable that increasing the complexity of the model increases ones insight into processes operating within the real system, or that the complexity leads to improved predictions. On the other hand, the increased complexity makes the model appear more like the real system and adds to the confidence of the interested community that the model reflects reality. The mark of a good model is that it is just complex enough to capture the essence the system.

In analyzing the Motorola/Honeywell Superfund site we created a simplified one-layer groundwater model of both flow and contaminant transport to represent the alluvial aquifer. As we will show, this model provides insight into the processes at the site. We modeled the movement of TCE and associated degradation products—DCE and vinyl chloride.

In 1996, Motorola created groundwater flow and transport models covering the area from the 52<sup>nd</sup> Street facility, to just west of OU2. In 1999, Honeywell created a groundwater flow model of the OU2 site; they extended the model east beyond the Honeywell facility but not as far as the Motorola facility. A regional groundwater flow model is being built by R. F. Weston Inc for the ADEQ; work started in 1998 and a final report on the groundwater flow model was issued in August, 2000. The Weston model extends from Priest Drive west to 99<sup>th</sup> Avenue, and from Camelback Road south to Dobbins Road. In 1999, Motorola extended their groundwater flow model grid to cover the Salt River. Motorola is currently working on a revised transport model that was presented to us in August 2000, however, to date this work has not been provided for a formal review. The extent of each model is shown in Figure 4.1, which shows that comparing results from the models is not easy, because of the different sizes and orientations.

### 4.1 WESTON/ADEQ REGIONAL MODEL

The Weston model covers an area of 18 miles by 10 miles (Roy F. Weston, 2000). The model has 144 columns and 80 rows, each cell is square—660 feet by 660 feet. The original Weston model had 3 active layers. The model parameters, such as the tops/bottoms of layers and the hydraulic conductivity values, are uniform over large blocks. The Weston model is regional in nature; it does not have either the site-specific detail or small-scale variations of the Motorola and Honeywell models.

#### **4.1.1 Model Code and Computer Software Used**

We ran the Weston groundwater flow simulations using MODFLOW (McDonald and Harbaugh, 1988) and Groundwater VISTAS® version 2.2 (Rumbaugh, 1998). MODFLOW is a modular, three-dimensional finite-difference groundwater flow model developed by the U.S. Geological Survey; it is widely used and accepted by the groundwater modeling community in North America. Groundwater VISTAS is a graphics pre and postprocessor that is used to create MODFLOW input files and display the model output.

#### **4.1.2 Physical Parameters Used in the Model**

The Weston model uses as boundary conditions constant-head cells in the northeast (elevation 1130 feet) and southwest (elevation 950 feet). The Salt River runs from east to west in the model and has an elevation of 1140 in the east, and 960 feet in the west. The river in the model is generally 10 feet deep and is simulated with a streambed of variable hydraulic conductivity. These boundary conditions simulate groundwater flow from east to west.

Constant head boundaries have the peculiar property that they can supply an unlimited amount of groundwater. The amount of groundwater moving into or out of the boundary is determined by the aquifer properties near the boundary—the transmissivity, and the gradient in hydraulic head. In other words, Darcy's law, that depends upon the transmissivity and gradient in hydraulic head, restricts the flow into or out of the constant head boundary. A word of caution is that pumping near a constant head boundary can induce flow from the boundary that is unrealistic.

Another facet of using constant head boundaries in the models is that the transmissivity of the aquifer determines how much groundwater flows through the system. The flow is not determined by inputs from the modeler. As suggested above, the direction, velocity and quantity of groundwater flow is determined by head differences imposed by the constant head boundaries and the transmissivity of the aquifer.

#### **4.1.3 Hydraulic Conductivity**

Within the model hydraulic conductivity values vary spatially within each of the three model layers. The changes in values appear to be based on aquifer tests, but there is no reference to the original data. The blocks of uniform conductivity are rectangular; they do not appear to be based on the geology. It would have been better to 1) use uniform values with different simulations using low, high, and most probable values, or 2) use actual data values where they are available and interpolate values for other cells. The conductivity values are multiplied by the saturated aquifer thickness to obtain transmissivity values. The thickness of the aquifer is obtained from arrays that map the top and bottom of the saturated zone.

Leakage parameter values vary spatially; again, the aerial variations appear to be unnaturally rectangular. There is no supporting documentation to justify their distribution.

#### **4.1.4 Summary of the ADEQ Groundwater Flow Model**

The ADEQ/Weston model covers more than the area of interest; it could be extended north to the mountains, that form a natural hydrogeological boundary. The southern boundary could be moved north, so that the Salt River forms the edge of the model. The model is too large and coarse to include the effects of the bedrock high near the Honeywell facility. This feature should be added to the model.

The model is continually being updated and refined; the current version has 5 layers. We could use this model to help set our boundary conditions, as our model covers a smaller area.

## **4.2 1996 MOTOROLA MODEL**

This 1996 Motorola model covers an area 20,000 by 40,000 feet—4 by 8 miles. It has 78 columns by 123 rows. The model has variable grid cell dimensions; the smallest cells are at the OU1 and OU2 pumping centers. The model has 22 layers, and a total of 211,068 cells, of which 139,403 are active.

Motorola also prepared a 33 layer version of the model in 1999 that included the Salt River. The model has not been documented; however, MODFLOW files produced from the model were received and transport results from the 1999 model have been discussed at meetings. Output contours have also been presented at meetings. Since the 1999 Motorola model has not been reviewed, this section provides a discussion of the 1996 Motorola model only.

### **4.2.1 Model Code and Software**

Groundwater flow simulations were originally conducted using TARGET, a propriety code owned by Dames and Moore, Inc (D&M). This code is three-dimensional, but it is limited to having individual layers with constant elevations for both the top and bottom—uniform-thickness horizontal layers. This feature causes there to be more layers than in the other models. The larger number of layers allows the bedrock surface to be defined in detail. The data were converted to run in MODFLOW (McDonald and Harbaugh, 1988). Input/output graphics were created in VISUAL MODFLOW®, (Waterloo Hydrogeologic, Inc). We ran the model using both GROUNDWATER VISTAS and VISUAL MODFLOW.

### **4.2.2 Physical Parameters Used in the Model**

The 1996 Motorola model grid covers both the Motorola 52<sup>nd</sup> Street and Honeywell facilities and the OU2 pumping center, but the model does not include the Salt River. Groundwater head contours and velocity vectors show the impact of the bedrock high that underlies the Honeywell facility. The no-flow and constant-head cells around the edges of the model control the direction of groundwater flow—east to west.

### **4.2.3 Hydraulic Conductivity**

Much like in the ADEQ/Weston model the hydraulic conductivity values in the 1996 Motorola model are varied spatially within each of the model layers. The distribution of hydraulic conductivity values is probably based on aquifer tests, but there is no reference to the original data. The blocks of uniform conductivity are rectangular and do not appear to be geologically controlled. This model needs to be run with the new hydraulic conductivity values obtained from the OU2 well tests.

### **4.2.4 Leakage between layers**

Leakage parameter values between layers vary spatially; again, the spatial variations appear to be unnaturally rectangular. There is no supporting evidence to justify their distribution.

#### **4.2.5 Groundwater Levels from the Steady State Flow Model**

Groundwater flow is from east to west, and is controlled by constant head boundary conditions. The capture zone from OU2, developed for steady-state flow conditions, indicates that contaminants will be captured from both Motorola and Honeywell facilities.

#### **4.2.6 Summary of the Motorola Model**

The 1996 Motorola model covers most of the area of interest. The model has been used to generate capture zones for the OU2 recovery system. The model shows capture from both the Motorola and Honeywell facilities. The model shows the importance of the bedrock ridge at the Honeywell facility. The TARGET transport model shows general agreement with plumes shown in figures 3.3 and 3.4.

### **4.3 HONEYWELL/ENVIRONMENTAL SIMULATIONS MODEL**

This model is smaller than the 1996 Motorola model; it covers a smaller area. The model includes the OU2 pumping center and the Honeywell site. Groundwater level contours, taken from the 1996 Motorola model, are used as constant-head boundaries to the east and west of the model domain.

The Honeywell model covers an area 5 miles east to west and 4 miles north to south. It has 134 columns and 188 rows, and has 4 layers. There are 100,780 cells, of which 87,400 are active. The three OU2 pumping wells are included in layers 1 and 2; they are simulated as 6 wells in the model—two wells in layers 1 and 2 at each location. The patterns of hydraulic conductivity are the same in layers 1 and 2. The hydraulic conductivity values are uniform in layers 3 and 4— $5.0 \times 10^{-3}$  ft<sup>2</sup>/day. The leakage parameter values are uniform between layers— $1.0 \times 10^{-3}$  ft/day.

#### **4.3.1 Model Code and Computer Software Used**

The model data were prepared in GROUNDWATER VISTAS, the model is run in MODFLOW, and the output data were graphed in GROUNDWATER VISTAS.

#### **4.3.2 Groundwater Levels from the Steady State Flow Model**

Groundwater flow is from east to west and is controlled by the boundary conditions. The capture zone from OU2 does not cover the Honeywell facility; however, an additional well should correct this problem. When we inserted the Motorola conductivity values into the Honeywell model, the steady-state capture zone does cover the Honeywell facility. The comparisons of conductivity values and resulting capture zones are shown in Figure 4.2 and the two capture zones in Figure 4.3. Figure 4.3 shows the capture zones that result from varying the uniform hydraulic conductivity values in the same model. Raising the bedrock ridge elevation causes groundwater to flow around the Honeywell Facility and leaves a stagnant zone below the southwest part of the facility.

#### **4.3.3 Summary of the Honeywell Model**

The Honeywell model covers most of the area of interest. Because of its smaller area, constant head boundaries are used to simulate groundwater flow beyond the model domain. These boundaries exert too much influence over the groundwater flow within the area modeled. Honeywell, which used somewhat different hydraulic conductivity values from Motorola, indicated that the OU2 capture zone does not include

the Honeywell facility site. The Honeywell model indicates that an additional well is needed to the south of the proposed OU2 wells.

Monitoring and testing of the OU2 wells will allow refinement of the range of hydraulic conductivity values. Both models show that a large part of the contaminants from Motorola will be captured by the OU2 wells. Monitoring should show if an additional well is required to capture contaminants from the Honeywell facility. Additional information on the nature of the bedrock high should also be available at a later time.

#### **4.4 EFFECTIVENESS OF OU2 TREATMENT SYSTEM BASED ON THE HONEYWELL AND MOTOROLA MODELS**

Both the Honeywell and 1996 Motorola models assumed steady-state conditions in determining their zone of capture. Steady-state assumptions result in the maximum extent of the capture zone. Flowlines are then calculated based on the resulting steady-state water table contours. Arrows on the flow lines indicate the time of travel for contaminant particles; the arrows are spaced at one-year intervals (Figure 4.2).

##### **4.4.1 Effectiveness during Steady-State**

The Motorola analysis shows that the flowlines/capture-zone will capture both the contaminants that have escaped past OU1 prior to the start of pumping at OU1, and contaminants from the Honeywell facility at steady-state (i.e., infinite time). The Honeywell model, using different conductivity values, shows that contaminants from the Honeywell facility may not be captured by OU2. Installing one or more additional wells southeast of the proposed OU2 wells would correct this, should it be a problem.

##### **4.4.2 Effectiveness During System Start-Up**

There is some evidence from the maps of TCE contours that contaminants have already passed beyond the site of OU2. Contaminant movement beyond OU2 may still continue until the system becomes fully operable. The actual growth of the cone of depression and capture zone will be considerably less than the steady-state prediction for some period. The time it takes for the cones of depression for each extraction well to intersect and block contaminant transport beyond OU2 can be calculated as follows:

$$r_o^2 = 2.25Tt/S$$

where

$r_o$	=	radius of cone of depression
$T$	=	Transmissivity, ft <sup>2</sup> /day.
$t$	=	time, days
$S$	=	Storage coefficient

If we assume: 1) a saturated thickness of 100 ft; 2) a hydraulic conductivity of 100 to 200 ft/day, (transmissivity of 10,000 - 20,000 ft<sup>2</sup>/day); 3) storage coefficient of 0.20; then the radius of the extent of the cone of depression from the OU2 wells after 1 year is approximately 6,000 to 9,000 feet—1 to 2 miles.

The calculations show that it takes 1 to 2 years for the capture zone to extend to the width of the plume. A contaminant transport model would be required to make more accurate calculations and produce maps for the early years of operation.

#### 4.4.3 Groundwater Velocities

Groundwater velocities upstream of OU2 can be estimated as follows:

$$v = (K/n) * (h_1 - h_2) / L$$

where:

$v$  = groundwater velocity ft/day  
 $K$  = hydraulic conductivity ft<sup>2</sup>/day  
 $n$  = porosity  
 $(h_1 - h_2) / L$  = hydraulic gradient

Inserting values into this equation suggests that the velocity is approximately 1.0 ft/day—365 ft/yr. Increasing conductivity to 200 or 300 ft/day doubles or triples this velocity.



## 5.0 THE HYDRODYNAMICS/EPA GROUNDWATER MODELS

The Hydrodynamics Group also developed groundwater flow and transport model based on the available data. The purpose of the model was to simplify the data used so that the sensitivity to various parameters could be assessed and “what-if” scenario’s “ could be run without major delays caused by slow data entry and long run times.

### 5.1 MODELING BACKGROUND

A groundwater model is a numerical code designed to solve the groundwater flow equation. The flow equation is a partial differential equation that describes hydraulic head, as the dependent variable, everywhere in the system.

Hydraulic head in a groundwater system is also important because it allows one to describe the flow of groundwater by applying Darcy’s law (see above). Darcy’s Law states that the gradient in hydraulic head when multiplied by the hydraulic conductivity gives the flux of groundwater. Darcy’s Law specifies that the flow of groundwater is in the direction of the hydraulic gradient.

A groundwater transport model is a numerical code that solves two coupled partial differential equations for flow and solute transport simultaneously. Conceptually the procedure is as follows:

The flow equation is solved for hydraulic head everywhere within the system at some particular time; Darcy’s Law is applied and the groundwater flow vectors are computed everywhere at the same time; Using the groundwater flow vectors the transport equation is solved which describes the concentration of some solute of interest, for example TCE, everywhere at the same time; and Then time is incremented, and the process is repeated.

The numerical procedures to solve the equations were first implemented in the 1960s and 1970s (Pinder and Bredehoeft, 1968; Bredehoeft and Pinder, 1972). The procedures are now well known even for three space dimensions.

The codes are quite explicit in their descriptions of the conceptual model created by the hydrogeologist. A number of parameters must be specified everywhere within the model domain; in general one must specify:

Flow—hydraulic conductivity (or transmissivity), and specific storage (or storage coefficient); and  
Quality—porosity, and dispersivity.

Partial differential equations cannot be solved without boundary conditions. Mathematically the boundary conditions consist of specifying on the boundary of the area of interest 1) either some value of the head, or the gradient in the head for the flow equation, and 2) some value of solute concentration, or a gradient in solute concentration for the quality equation. The mathematics of this sound complicated, but in actual practice there are natural boundaries for most systems. For example, the aquifer is contained within a complex of much less permeable (impermeable) rocks; this indicates an impermeable boundary at the edge of the aquifer.

How one models hydrologic features such as 1) intermittent streams and 2) changes in pumping regimes is less obvious. However, there are well-developed methods to handle these features.

## 5.2 THE CONCEPTUAL MODEL

In the entire modeling procedure the conceptual model is critical to the process; its importance should not be overlooked. The conceptual model is the vision of the system that the modeler translates into a numerical model. The resulting model is an abstraction of reality. The conceptual model depends on the skill of the modeler. Often it is hard to evaluate whether the modeler had a correct vision of the system in his conceptual model; this is a matter of judgment. Numerical models produce output whether the conceptual model is good or bad.

In evaluating model results after the fact, a post audit, more often than not the system did not behave, as the model predicted (Konikow and Bredehoeft, 1992). Often this resulted from scenarios of development that were not modeled. However, in other systems the model predictions were poor. In evaluating the poor predictions, it is unclear whether the error was in the conceptual model or in a wrong parameter distribution. Often a poor conceptual model leads to a poor parameter selection.

We wish to emphasize this point. The selection of the conceptual model is critical to the modeling process. The conceptual model is an *a priori* decision on the part of the modeler. It is a matter of judgment and skill. It is the conceptual model that usually makes the difference between a good or bad model.

### 5.2.1 The Weston/ADEQ Model

This model used 5 layers to simulate the three alluvial units and did not include bedrock units. The model covers a larger area than the study area, where we do not appear to have units MAU and LAU. The impacts of pumping, leakage from the Grand Canal and the Salt River are included. The cells are 660 ft x 660 ft and the model is focused on regional impacts rather than details at the Honeywell or Motorola facility sites. We could use the results from this model to set boundary conditions around our area of study. Results from our models of the study area can also be incorporated into the regional model.

### 5.2.2 The 1996 Motorola Model

The TARGET model was converted to MODFLOW format and tested. The number of layers should be reduced for the MODFLOW model. This would substantially reduce the time required to change data and to run the model. Boundary data from the WESTON model could be used in this model. Without reducing the layers in the model it will not be possible to determine the sensitivity of the model to various parameter changes, such as the ridge configuration or variations in hydraulic conductivity, in a timely manner.

### 5.2.3 The 1999 Honeywell Model

This is essentially a simplified and reduced-area model of the 1996 Motorola model built to show the effectiveness of the OU2 Remedial Operating system. It is a steady-state model and needs to be expanded in area and to transient conditions. It also needs a transport component. Now that Honeywell has completed a conceptual model of site hydrogeology, the groundwater flow model could be enhanced.

### 5.2.4 Bedrock Ridge

The Motorola and Honeywell conceptual models treat the bedrock ridge differently. Motorola assumes that the bedrock ridge is high enough and continuous enough to divert groundwater flow around the Honeywell facility site. Honeywell's conceptual model assumes that the ridge is not continuous and that contaminants

from Motorola have been carried across their site through these saddles. The drilling has shown that most of the “saddles” do not exist. Honeywell counters that they exist between the newer test holes.

Both models assume “steady-state” flow conditions occur. In reality water levels have fluctuated over the past 20 years. In wet years the high water table could result in some flow under (instead of around) the Honeywell site. In dry years the ridge would provide a more significant flow barrier than used in the steady-state assumptions. We could use the Weston regional model to simulate water levels over the past 20 years (actual records are not very complete) and compare these to the bedrock contour maps.

### **5.3 THE HYDRODYNAMICS GROUP MODEL**

We have chosen to represent the system as one layer of varying thickness. We neglect flow and transport in the bedrock; we treat the bedrock as impermeable. Using one layer is a simplification compared to both the Motorola and Honeywell models. We will show that the one layer model provides good insight into the system.

#### **5.3.1 Model Parameters and Boundary Conditions**

Numerical groundwater modeling requires that one define a set of parameters that explicitly describe the aquifer being modeled. This information defines:

- The geometry of the aquifer—thickness and dimensions;
- The properties of the aquifer—hydraulic conductivity, porosity, dispersivity;
- The aquifer boundary conditions; and
- The important sources and sinks for contaminants.

#### **5.3.2 Aquifer Geometry**

The bottom of the aquifer has been defined as the bedrock surface. However, the bedrock is not impermeable, and is contaminated with TCE. However, the hydraulic conductivity of the bedrock is at least two orders of magnitude lower than the alluvial aquifer. The porosity of the bedrock is from fractures and also is much lower than the alluvial aquifer. We modeled the bedrock as impermeable. We judge that neither the movement of dissolved TCE or the amount of dissolved TCE in the bedrock is significant in comparison to that in the alluvial aquifer. We chose to neglect flow and transport in the bedrock.

Figure 5.1 is our contour map of the top of the bedrock. The data are sparse outside of the Washington Street corridor both to the north and south. The bedrock ridge is a prominent subsurface feature beneath the Honeywell facility.

The saturated aquifer thickness is taken as the difference between the bedrock surface and the water table. Figure 5.2 is our map of the aquifer thickness.

### ***Transmissivity***

The transmissivity at any point in space (in our case  $x, y$ ) can be defined as the average hydraulic conductivity multiplied by the saturated thickness of the aquifer. We examined the hydraulic conductivity available for the area; it varies widely. However the range appears to be between 50 and 200 feet/day. Figure 5.3 is a map of the aquifer transmissivity; Figure 5.4 is a map of the hydraulic conductivity.

The area of our investigation is near the eastern margin of the Salt River Valley basin. The map of hydraulic conductivity suggests that the value for much of the area is approximately 100 feet/day. We decided on a decision rule to describe the hydraulic conductivity of the alluvial aquifer. Where the saturated aquifer is 50 feet thick, or less, we used a hydraulic conductivity of 50 feet/day. Where the aquifer is greater than 50 feet thick we used a hydraulic conductivity of 100 feet/day.

### ***Porosity***

The porosity of the alluvial aquifer is harder to measure. It can be measured on core samples in the laboratory, but usually in an alluvial aquifer coring does not work well especially in the sand and gravel deposits that are most transmissive. Porosity is one of the parameters that we varied in the modeling. We varied the porosity between 0.2 and 0.3—20 to 30% porosity. We will show the sensitivity of the model results to porosity.

### ***Dispersivity***

The dispersivity of the alluvial aquifer controls the spread of the plume both in the direction of groundwater flow (longitudinal dispersion) and at right angles to the flow (transverse dispersion). Solving the transport equation is more difficult numerically than solving the flow equation. Most transport models are a numerical compromise. Some do not conserve the mass of contaminant well. Most finite-difference solutions introduce numerical dispersion.

We used a version of the model JDB-MOC (1995), this version uses an explicit finite-difference solution technique for the calculation of contaminant transport. The explicit version does well in maintaining the mass of the contaminant; however it introduces numerical dispersion. It is difficult to know exactly how large the dispersivity is because of the numerical dispersion. We judge the longitudinal dispersivity to be approximately 100 feet and the transverse to be 1/3 of the longitudinal.

### ***Model Grid***

We used a model grid of 1000 by 1000 feet. Figure 5.2 shows our model grid superimposed on the aquifer thickness.

### ***Aquifer Boundaries***

The aquifer pinches out just east of the Motorola 52<sup>nd</sup> Street facility and along the hills to the east of the airport. Along this boundary we treated the model boundary as impermeable. The north and south boundaries are approximately along flow lines and were treated as impermeable.

### ***Model Boundaries***

We used constant flow boundaries, not constant head boundaries, to create inflow and outflow from the model. The inflow is distributed along the eastern and northeastern portion of the model. The outflow is distributed along the western edge of the model. We assumed no recharge over the area of the model—all the flow comes in and out the boundaries. We modeled steady-state flow, i.e., inflow equals outflow. The flow through the model is approximately 9,500 acre-feet/year (13 cubic feet per second). Along the eastern edge of the model the recharge is not uniformly distributed—10% of the recharge comes from the bedrock highland to the east; 90% comes from extension of the alluvial valley to the northeast. Along the western edge of the model the discharge is distributed more or less uniformly between McDowell Road and Buckeye Road—the discharge is centered on Van Buren Street.

### ***Sources and Sinks of Contamination***

We assumed that there were sources of contamination at the Motorola 52<sup>nd</sup> Street facility and the Honeywell facilities. We adjusted the TCE source strengths in the model to generate TCE concentrations comparable to that observed beneath the two facilities. We held these source strengths constant in time, with one exception. Once OU1 was in place and operating at the Motorola 52<sup>nd</sup> Street facility we assumed the facility was eliminated as a further source of contamination—OU1 was 100% effective. Significant contributions could be made from DNAPL flow along the bedrock interface and from dissolution. However, we did not analyze this because of the lack of DNAPL data for the site.

We simulated the effectiveness of Operating Unit 2 (OU2) in removing the contamination from the aquifer.

## **5.4 CHEMICAL BIODEGRADATION**

TCE is known to degrade bio-chemically. One common way to generalize the reaction is as a first-order chemical reaction. The best known of the first-order reactions is radioactive decay. First-order reactions are characterized by their half-life. A first-order reaction has the form of:

$$C = C_0 e^{-at/\lambda}$$

where

C	=	the concentration of the chemical at any time t
C <sub>0</sub>	=	the initial concentration of the chemical at time 0.0
a	=	a constant, 0.6931472
t	=	some time
λ	=	the half-life of the reaction

In the case of Phoenix we want to include three decay reactions—1) TCE to 1,2 DCE, 2) 1,2 DCE to vinyl chloride, and 3) the decay of vinyl chloride. Each of these reactions can have a different half-life. However, the roles of competing electron acceptors and electron donors were not addressed in the Phoenix model. TCE degradation primarily occurs under anaerobic conditions, whereas 1,2 DCE degradation usually occurs faster under aerobic conditions. Vinyl chloride (VC) degradation occurs almost exclusively under aerobic conditions. Information on dissolved oxygen and other competing electron acceptors and electron donors would be needed to properly estimate rate constants.

## 5.5 NUMERICAL MODEL

The Hydrodynamics Group used the numerical model JDB-MOC developed by John Bredehoeft at the USGS, (Bredehoeft, 1995). This model is based upon the flow model JDB2D/3D (Bredehoeft, 1991) and is a modification of the original MOC program for microcomputers. JDB-MOC is more stable, has a better mass balance, and runs faster than the original MOC program. The Hydrodynamics Group is also more familiar with the code so it is easier to modify and add features. The model was modified to transport three chemicals simultaneously—TCE, 1,2 DCE, and vinyl chloride. The decay of TCE is the source for 1,2 DCE; the decay of 1,2 DCE is the source for the vinyl chloride.

The version of the model used solves the transport equations using an explicit finite-difference method (Zheng and Bennett, 1995).

## 6.0 MODEL CALIBRATION

Groundwater models are calibrated by matching the model output to known groundwater conditions, for example—1) the water table at some time, and 2) the contaminant (TCE) distribution at some time. Matching to both a water table and a TCE distribution provides a redundancy in the calibration that further constrains the model. In other words, the models are more constrained when we have both a head distribution (the water table) and a contaminant distribution that must be matched. This calibration procedure has been referred to as history matching—a better description of the calibration process.

The history matching procedure can be applied in several ways. One way is to compare head and/or concentration histories at individual wells within the system. In many situations the data are lacking or sparse. Another way to make the history match is to map the head and/or the contaminant distribution at some time and then compare the model output to the maps of head and contamination.

In matching the model output to the maps of observed head and contamination one looks at the pattern of model outputs versus the pattern of the observations. This is usually the more powerful of the history matching (calibration) methods. We used the pattern recognition procedure exclusively in calibrating our model.

Two procedures are used in history matching—1) trial and error, and 2) non-linear optimization. In either case some parameter, or set of parameters often the transmissivity, is varied until one obtains what he judges is a good fit between the model output and the observations. Both trial and error and optimization are widely used. Often trial and error provides more insight into the sensitivity of the model to the changes in various parameters. The Motorola and Honeywell conceptual models differ with regard to flow in the area of the bedrock ridge near the Honeywell facility (see Section 5.2). Whether the bedrock ridge is permeable or impermeable could have a large effect on groundwater flow and contaminant distribution. We tested both the effect of a permeable bedrock ridge and of an impermeable bedrock ridge on the contaminant plume.

### 6.1 HYDRAULIC HEAD

Our first task is to match the observed water table with the model-generated water table; Figure 6.1 is the model generated 1996 water table. This model output is for a condition where the bedrock ridge beneath the Honeywell facility is permeable. In this simulation the ridge has 25 feet, or more, saturated thickness over it.

Figure 6.1 can be compared with Figure 3.2—the observed 1996 water table. The model generally produces heads similar to that observed in 1996. The model generated water table produces flow to the southwest in the area between the Motorola and Honeywell facilities.

For our analysis we assume that the water table is stable in time. We use the 1996 water table without varying it with time. Making this assumption the groundwater flow vectors are constant in time.

### 6.2 TRANSPORT—RIDGE PERMEABLE

We first calculate a 40-year plume of contamination from the Motorola 52<sup>nd</sup> Street facility with the saturated thickness over the ridge thin, but still permeable. For this simulation the porosity is 0.25; there is decay of the TCE with a 40-year half-life. Figure 6.2 shows the resulting computed plume of TCE. The main plume

of TCE extends through the Honeywell facility and then southwest beneath Skyharbor Airport. There is contamination along Van Buren Street, but this is not the center of the plume.

Figure 6.3 shows a 40-year plume of TCE contamination from the Honeywell facility. There are two main sources of TCE from Honeywell—1) east of the bedrock ridge, and 2) west of the ridge. The Honeywell model generated plume extends to the west—west of the airport.

The combination of these two model generated plumes matches poorly with the observed TCE distribution. The centers of mass of the model-generated contamination is too far south.

### **6.3 TRANSPORT—RIDGE IMPERMEABLE**

We went through the same set of simulations except that we made the bedrock ridge impermeable. Figure 6.4 is a model generated TCE 40-year plume from the Motorola facility. The plume now extends westward just to the south of McDowell Road—between McDowell and Van Buren Streets. The plume swings southwestward once it passes the bedrock ridge. This compares much more favorably with the observations of TCE—Figure 3.2.

Figure 6.5 is a model generated TCE plume from the Honeywell facility. Contamination from Honeywell east of the ridge moves northwestward along the ridge. Once it is beyond the ridge it swings to the southwest. Contamination from Honeywell on the southwest side of the bedrock ridge tends not to move. There is groundwater flow shadow behind the ridge. There is no extensive plume of contamination from Honeywell on the western side of the ridge.

Figure 6.6 is a combined Motorola and Honeywell computed 40-year TCE distribution map with the ridge impermeable. We judge Figure 6.6 as the best representation of the observed TCE plume. The model suggests that the bedrock ridge acts as a barrier to groundwater flow.

Figure 6.7 is the water table that is generated by the model when the ridge is impermeable. The groundwater gradient steepens over the impermeable ridge because the ridge acts as a discontinuity. The match between the observed (Figure 3.1) and the model-generated (Figure 6.7) water tables is poor. However, when considering both the distribution of TCE and the water table we believe the ridge acts as an impermeable barrier to flow.

### **6.4 CONCLUSIONS**

For OU2 groundwater flow and contaminant transport the important feature is the bedrock ridge – assumptions about the ridge change the results enormously. A permeable ridge causes the Motorola plume to move to the SW across the Honeywell facility site. The Honeywell plume also moves to the SW and becomes larger than observed. An impermeable ridge causes the Motorola plume to swing north of the ridge and then west along Van Buren Street. Sources at the Honeywell facility north of the ridge move west and will be captured by OU2. Sources south of the ridge do not create a large plume, due to the “backwater” effect of the ridge. In general, contaminant contours match actual data more closely with an impermeable rather than permeable ridge.



## 7.0 MODEL RESULTS

Once the model was calibrated we used it to explore the effects of these process and aquifer properties:

- Biodegradation of TCE;
- Changes in porosity on the extent of the plume;
- Formation and degradation of 1,2 DCE;
- Formation and degradation of vinyl chloride; and
- Capture of contaminants by the OU2 treatment system.

Model results were compared to concentration contour maps produced from data collected from monitor wells (Section 3.0). However, note that these contour maps are based on a limited number of data points. A few more strategically placed wells could materially change the observed concentration contour maps.

### ***Biodegradation***

Biodegradation was added to the model of TCE transport. Figure 7.1 is a model generated TCE plume with a 10-year half-life for TCE. The plume does not extend westward with high enough concentration. It appears that the half-life is longer than 10 years.

Figure 6.6 was calculated with a 40-year half-life for TCE; 40 years appears to be much more appropriate. Degradation of 1,2 DCE was also modeled. This compound is a degradation product of TCE. A half life of 40 years produced the best fit with observed 1,2 DCE concentrations.

### ***Porosity***

The plume length is quite sensitive to porosity. Figure 7.2 is the computed plume of TCE with a 40-year half-life, and the aquifer with 20% porosity. Under these assumptions the modeled plume extends much further to the west than what is observed. A 25 and 30% porosity was also used in the model; 25% gave the best result. Figures 6.2 through 6.6 are calculated with 25% porosity.

### ***1,2 DCE and Vinyl Chloride***

Figure 7.3 is the computed plume of 1,2 DCE; the DCE is generated from TCE with a 40-year half-life. The 1,2 DCE also has a 40-year half-life. Figure 7.3 can be compared with Figure 3.3—the observed 1,2 DCE distribution.

The model does not generate the series of pods of either TCE or 1,2 DCE that the observed data indicate. For example, significant concentrations of 1,2 DCE were detected north of the Honeywell facility and Tiernay Turbines, but are not accounted for in the model. In general, the model-generated plumes are more continuous. The field data are invariably more noisy than the theoretical-models generate. The noise in the real data may be due to sampling and laboratory analysis error; or it may represent sampling from different depths in the aquifer; or it may represent a real variation in contaminant movement within the aquifer. This noise in the contaminant data is the subject of active research.

Figure 7.4 is a map of the vinyl chloride plume generated by the degradation of 1,2 DCE. The vinyl chloride is given a half-life of 4-years—10% that of both TCE and 1,2 DCE. Vinyl chloride is known to be much more volatile than either TCE or DCE. The model generated vinyl chloride distribution, Figure 7.4 can be compared to the observed distribution, Figure 3.4.

In the model results there is a hot spot of vinyl chloride that corresponds to the hot spot in the TCE and 1,2 DCE plumes between McDowell Road and Van Buren Street. The model indicates another hot spot beneath the Honeywell facility on the southwest side of the bedrock ridge. The highest observed concentrations of vinyl chloride are beneath the Honeywell facility southwest of the bedrock ridge, which does not match the model results.

### ***Operable Unit 2 (OU2)***

One of the procedures used to estimate the effectiveness of a pump and treat system is the capture zone analysis. In this analysis a flow model is used to designate the capture zone. The capture zone is a divide in the hydraulic head or the water table; inside this divide groundwater water moves toward a pumping well—in other words water within this divide is captured by the well. The cone of depression grows as a well continues to pump; therefore the capture zone is not stable in time. The usual procedure is to calculate the hydraulic head, or the water table, at infinite time when the cone of depression has reached its maximum value to determine the capture zone. At infinite time the groundwater system reaches a new equilibrium state in which there is no more change in head with increased time. This is the state with the maximum zone of capture. The capture zone analysis neglects dispersion that occurs in groundwater systems. The capture zone analysis does do not indicate how long pumping must continue to eliminate the contaminant.

Another procedure is to use a contaminant transport model to estimate the effectiveness of a pump and treat system. We simulated the operation of the OU2 pump and treat system. We introduced one pumping center, pumping at approximately 1800 gallons per minute continuously—4 cubic feet per second. Figure 7.5 is a steady state water table generated by the model with the well pumping. There is a cone of depression developed by the pumping.

We then start with the aquifer contaminated. We use the 40-year TCE plume shown in Figure 6.6 as our starting condition for the operation of OU2—this is the model-generated plume judged to be our best. Figure 7.6 shows the TCE plume after 10 years of pumping. A small amount of contamination has gotten by OU2, and is moving down the valley. Most of the TCE is being captured by the OU2 pumping.

Figure 7.7 is the TCE plume after 20 years of pumping. The model suggests a low concentration of TCE that has moved westward down the valley. The pumping has begun to move TCE from the Honeywell facility west of the bedrock ridge. In the model we maintain the Honeywell facilities both east and west of the bedrock ridge as sources of TCE contamination.

Figure 7.8 is the TCE distribution after 30 years of pumping. TCE that has moved westward beyond OU2 down the valley has degraded away. The TCE contamination after 30 years of OU2 operation is dominated by the sources at the Honeywell facilities. This may be a relict of the model maintaining the Honeywell facilities as a source of TCE—perhaps an unrealistic assumption.

Figure 7.9 is a model generated TCE distribution following 40 years of OU2 operation. One can see in this figure that the TCE from the Motorola facility is completely gone. The remaining TCE comes from the Honeywell facilities that are assumed to be a continuing source of TCE.

Maintaining the source of TCE contamination at Honeywell may be completely unrealistic in the modeling. The model does suggest that some effort to eliminate contamination beneath the Honeywell facilities is probably warranted. Pumping at OU2 will move contamination westward from the Honeywell facility unless it is eliminated as a source.

**Table 7.1: Effects of Model Parameters**

<b>Parameter</b>	<b>Effect</b>
<b>Porosity</b>	
20%	Plume moves too far
30%	Plume does not extend as far as data
25%	Plume extent matches data
<b>Biodegradation</b>	
TCE 10-year half-life	Plume does not extend far enough
TCE 40-year half life	Plume extent matches data
<b>Ridge</b>	
Permeable	Plume extends to SW, does not move along Van Buren, does NOT match data
Impermeable	Plume moves around ridge, Plume matches data

## 8.0 SUMMARY AND CONCLUSIONS

The following conclusions relative to the objectives presented in Section 1.0 can be drawn from the single layer Hydrodynamics Group model of groundwater flow and contaminant transport at the Motorola 52<sup>nd</sup> Street Superfund Site:

1. The effects of the bedrock ridge on contaminant flow:

Modeling TCE transport indicates that the bedrock ridge that underlies the Honeywell facilities is a barrier to groundwater flow. Once the ridge is treated as a barrier the main plume of contamination moves westward along Van Buren Street as the data indicate. Contamination from the Honeywell facilities west of the ridge tends not to move; there is little groundwater flow behind the bedrock ridge. The bedrock ridge explains why a contamination plume is not observed downstream of the Honeywell facility. Dames and Moore (1996) in their transport analysis for Motorola also found that the bedrock ridge was a barrier to flow.

2. Sensitivity of the model to various parameters:

The model was shown to be sensitive to biodegradation half-life. The half-life of the degradation reactions for TCE and 1,2 DCE were estimated to be 40 years; and the half-life for vinyl chloride was estimated to be 4 years. Within the scope of the present study, the model does a reasonable job of approximating the 1,2 DCE plume and to a lesser degree, the vinyl chloride plume. The model was also shown to be sensitive to hydraulic conductivity, and porosity.

3. Effectiveness of the OU2 treatment system:

The model indicates that the OU2 treatment system captures most of the contamination from both the Motorola and Honeywell facilities. It will probably require several decades of pumping if the contamination between OU2 treatment system and the Motorola and Honeywell facilities is to be cleaned up. However, if there are one or more DNAPL sources of TCE, the time for clean-up could be substantially longer. This indicates the importance of monitoring the central portion of the contaminant plume upstream of the OU2 treatment system and, if there are DNAPL or other sources, that they be addressed. If contamination remains at these facilities it will be drawn to OU2.

The capture-zone models from both Motorola and Honeywell show that the OU2 wells will ultimately capture the plume emanating from the Motorola and eastern edge of the Honeywell facilities. The Honeywell model suggests that OU2 may not be effective at their facility.

4. Estimated relative contribution of each party to the contaminant plumes:

The contribution of each site to OU2 contamination depends upon the ridge geometry and hydraulic conductivity, it also varies with time. Initially Motorola is the larger contributor, after 10-20 years Honeywell becomes the larger contributor, unless the source south of the ridge is treated first. After 30 years it appears that the Motorola plume will be mostly cleaned up and Honeywell will be the main contributor. Further modeling would be required to refine these estimates.

5. Possible future data gathering and modeling efforts:

The bedrock ridge is probably the most important factor controlling groundwater flow and contaminant transport around the Honeywell site and the OU2 treatment system. The borehole logs should be re-examined to determine the bedrock contact and then the surface should be contoured. Areas where additional boreholes are required can be identified. The alternative is to assume that the ridge is impermeable. It is possible that groundwater flowed over the ridge in the past during periods of high water levels. Water level data should be examined to determine if this has may have occurred. Predicted water levels from the Weston model could also be used to see if groundwater could have flowed over the ridge.

Once data from the OU2 treatment system well pump tests have been evaluated, it would be possible to model the effectiveness of the system more accurately. Specifically, whether another pumping well is needed to the south to effectively capture contaminants from the Honeywell facilities. Any other pump test data that provides hydraulic conductivity estimates would enhance the modeling efforts.

Additional water level and groundwater chemistry data, including parameters used for estimating biodegradation, and refined conceptual site models, including identification of layers or areas of different permeability in the alluvial aquifer, would also help refine the modeling efforts. A few more strategically placed wells could materially change the observed concentration contour maps. Careful review of the observed data and the interpolation/extrapolation methods used to prepare observed concentration maps would be useful.

Finally, a better understanding of current and past conditions at the Honeywell facilities, including the identification of possible spill/leak sites, contaminant concentrations, geologic conditions, groundwater flow, and the possible effects of jet fuels on TCE concentrations, could also be used to refine the models.

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## **FIGURES**



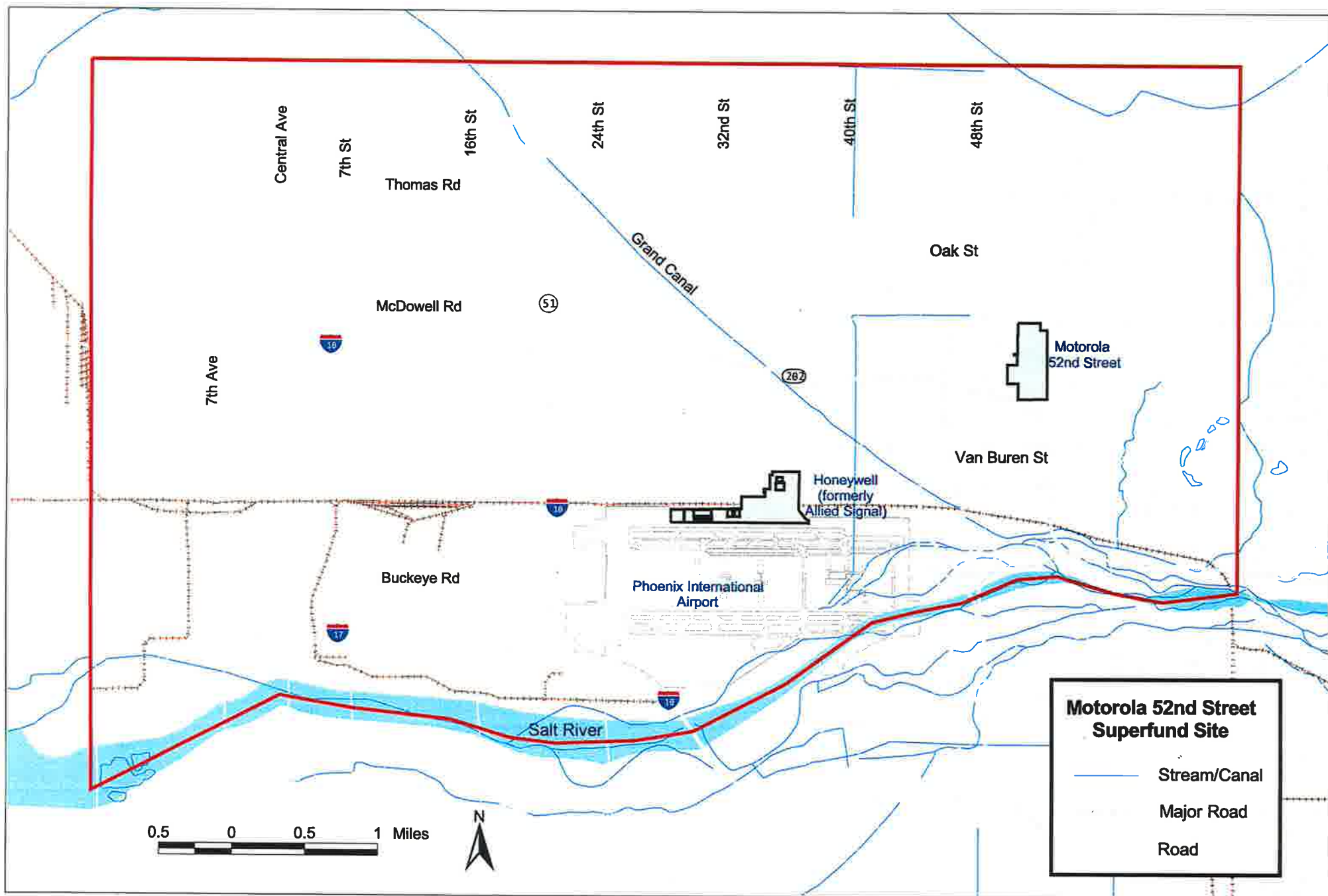


Figure 1.1 Location of the Study Area

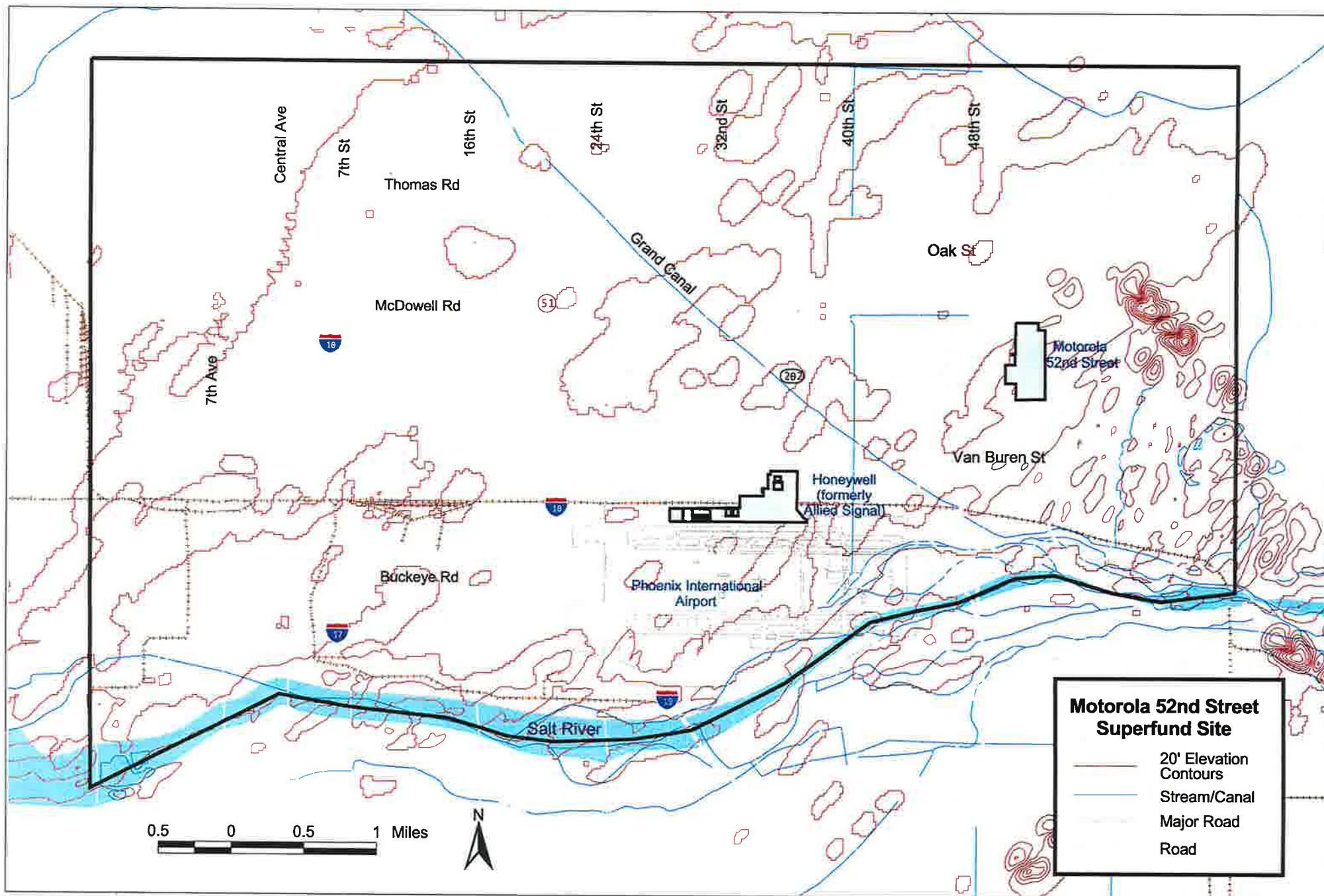


Figure 2.1 Topographic Contour Map

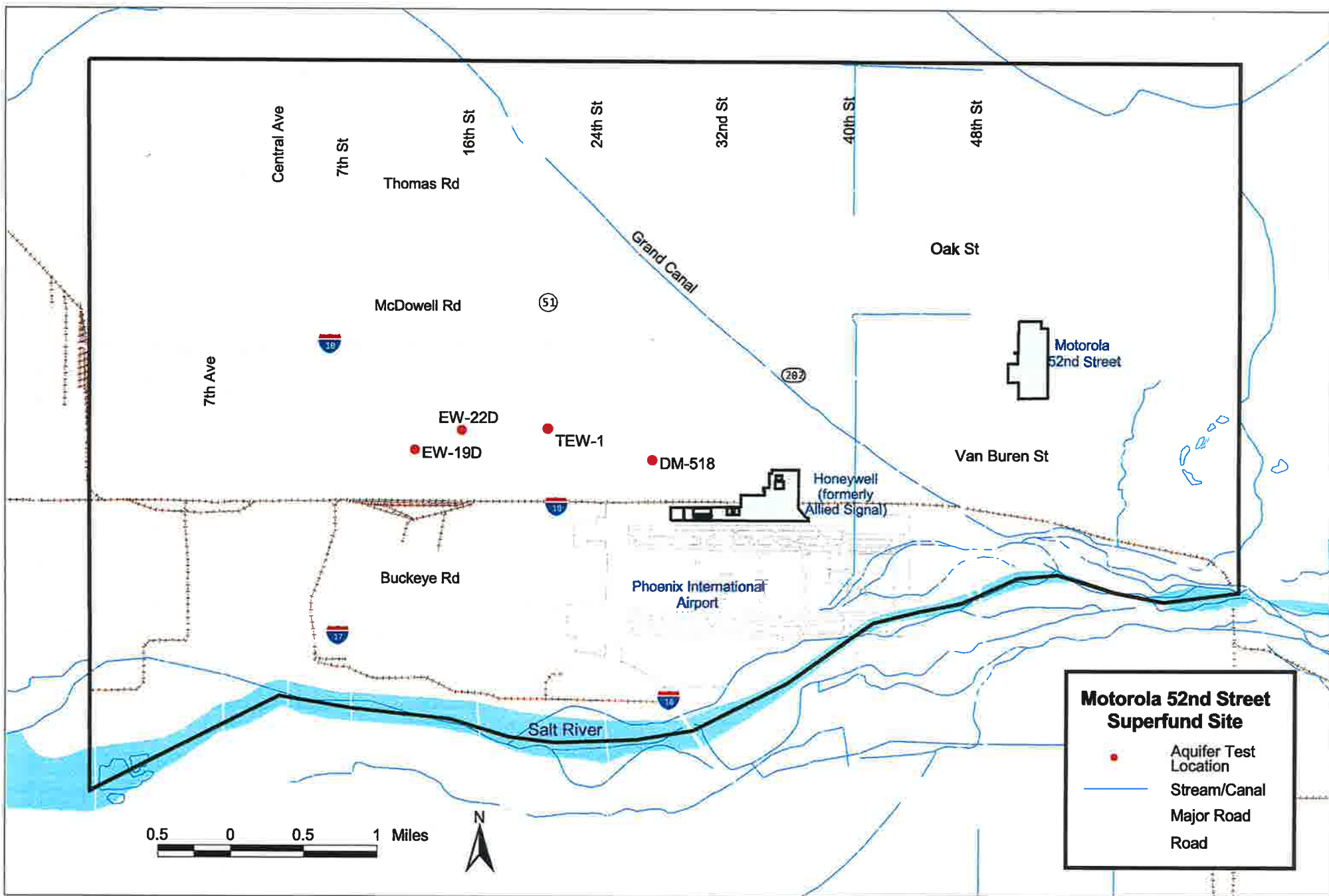


Figure 2.2 Aquifer Test Locations



96 Water Table—with data points

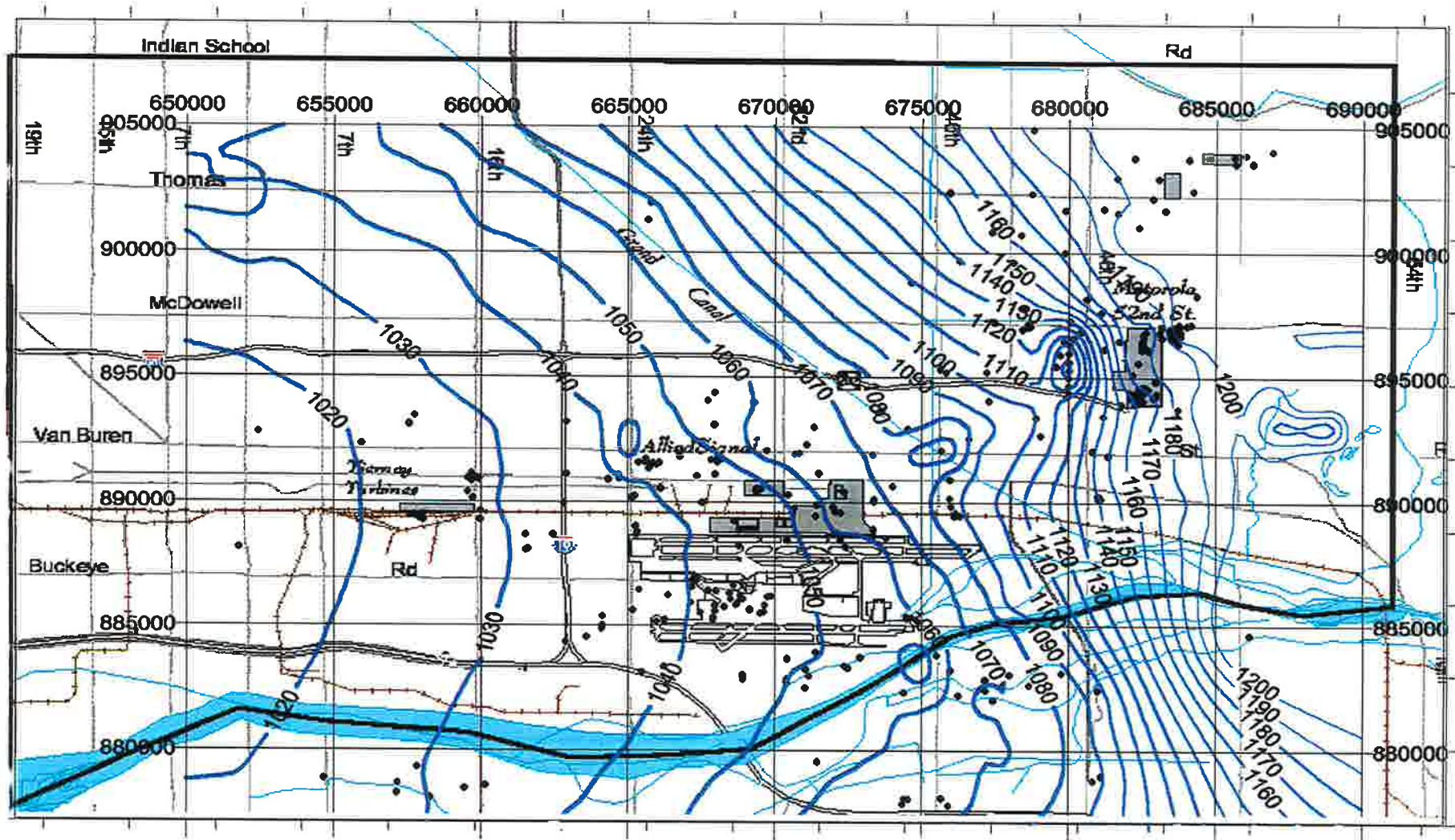


Figure 3.1 Water Table Contour Map, 4th. Quarter, 1996

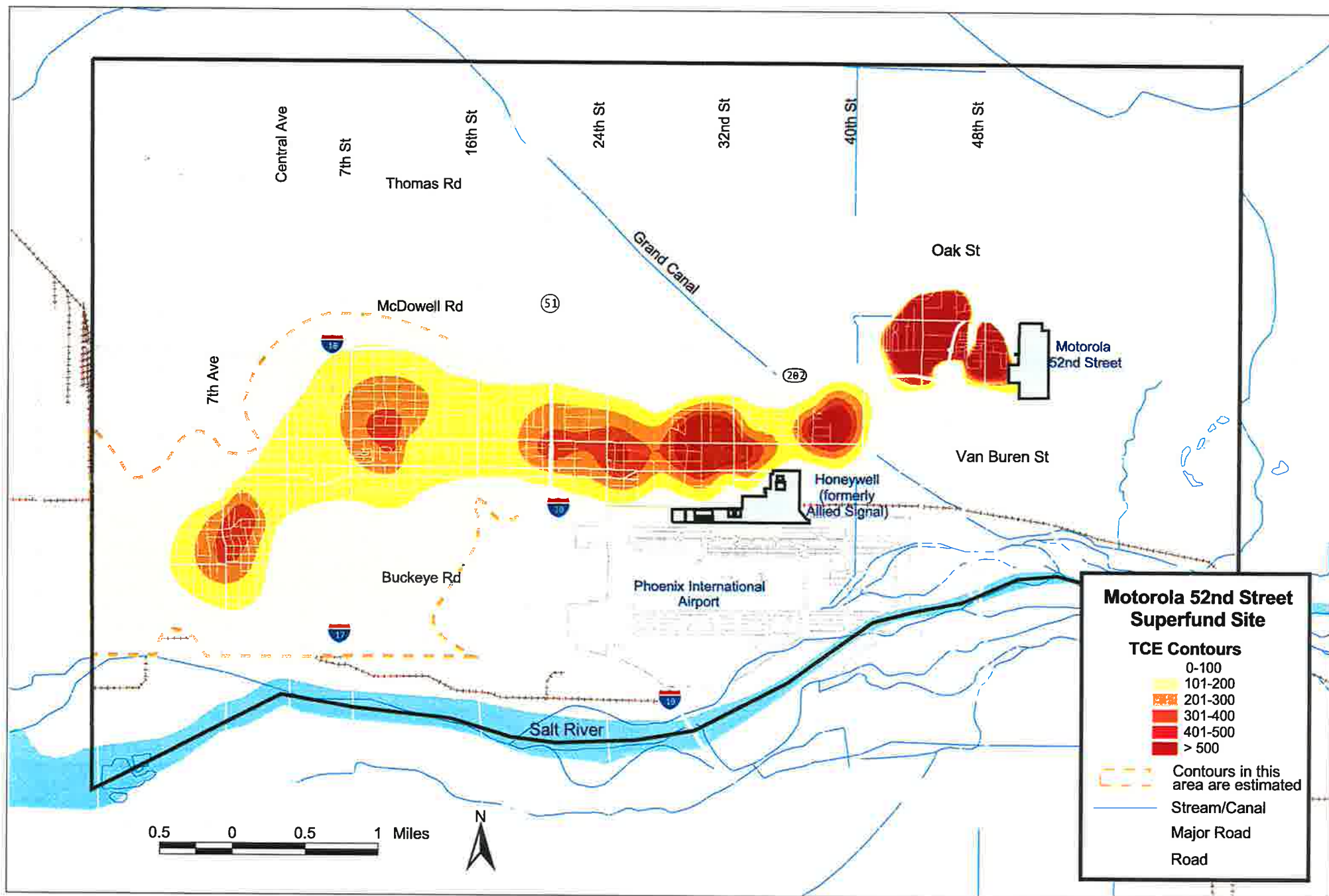
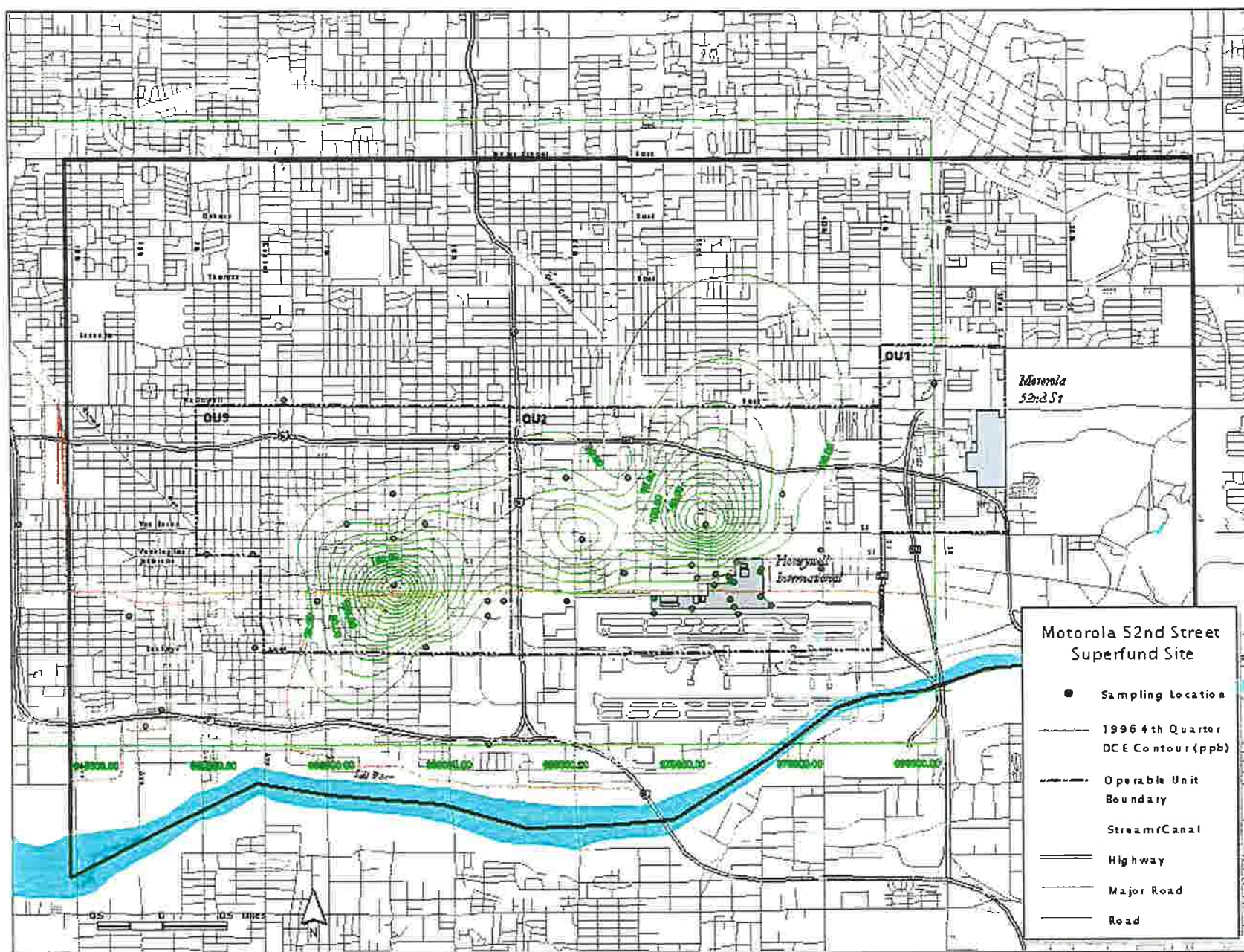


Figure 3.2 TCE Contour Map 4th. Quarter, 1996





**Figure 3.3 1,2 DCE Contour Map, 4th Quarter, 1996**

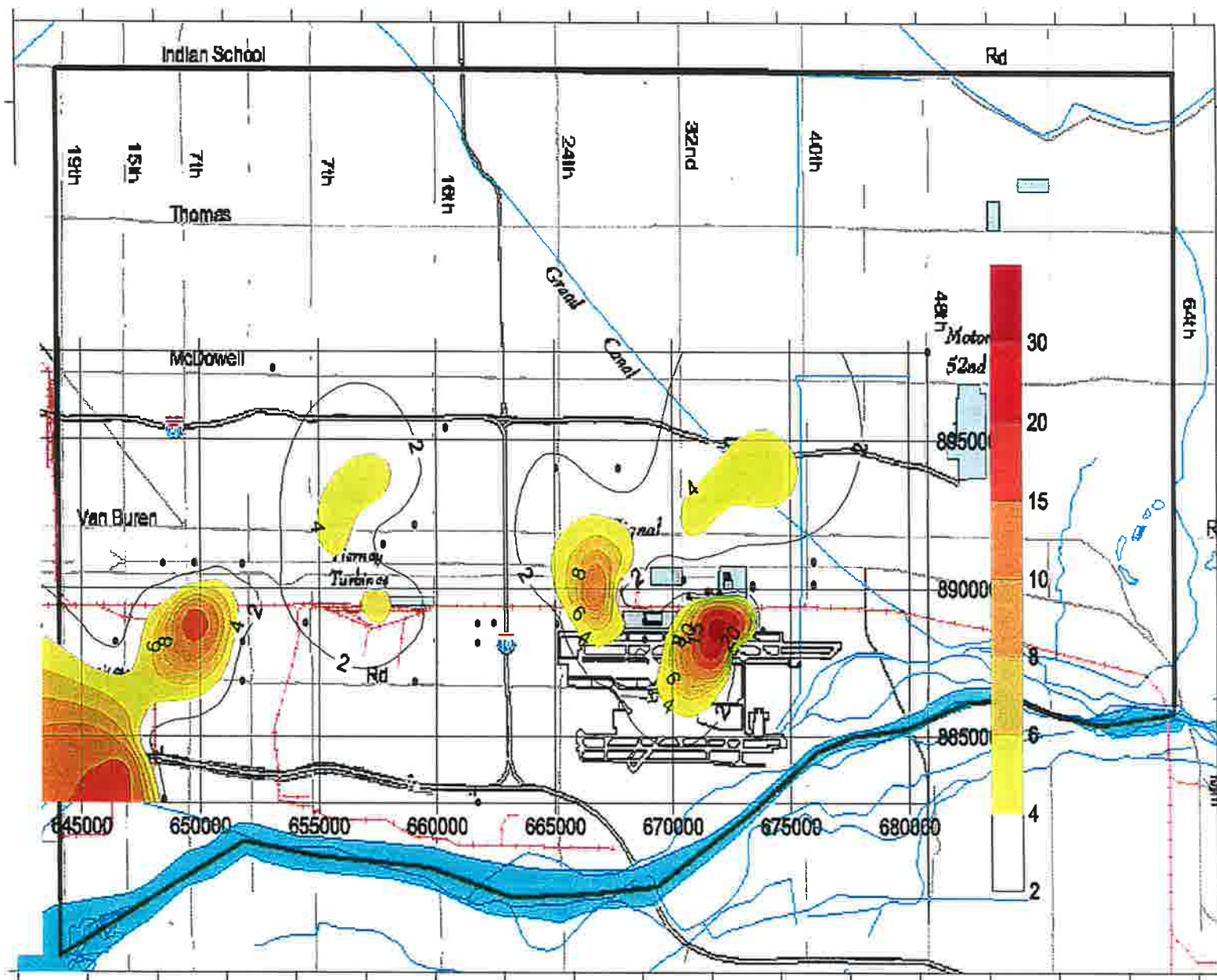


Figure 3.4 Vinyl Chloride Contour Map, 4th Quarter, 1996



**Weston/ADEQ model covers  
all of this map and extends  
10 miles westwards**

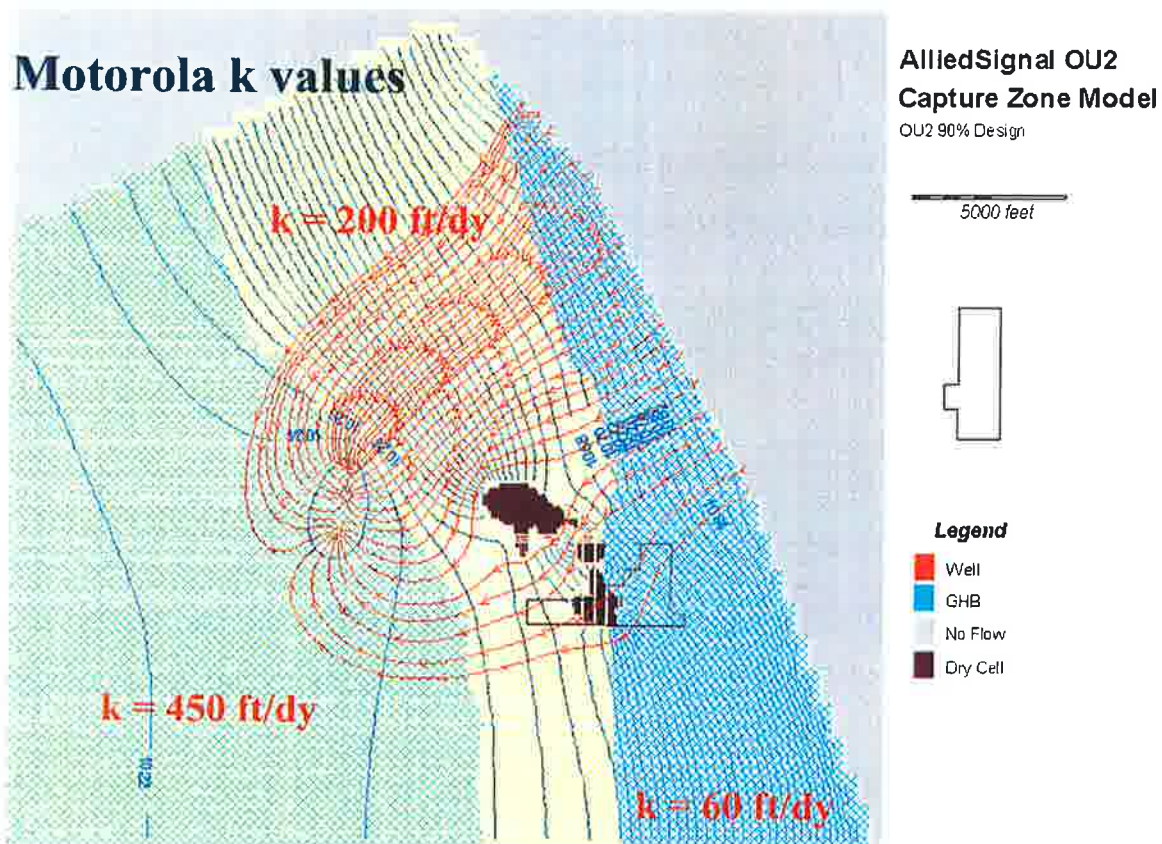
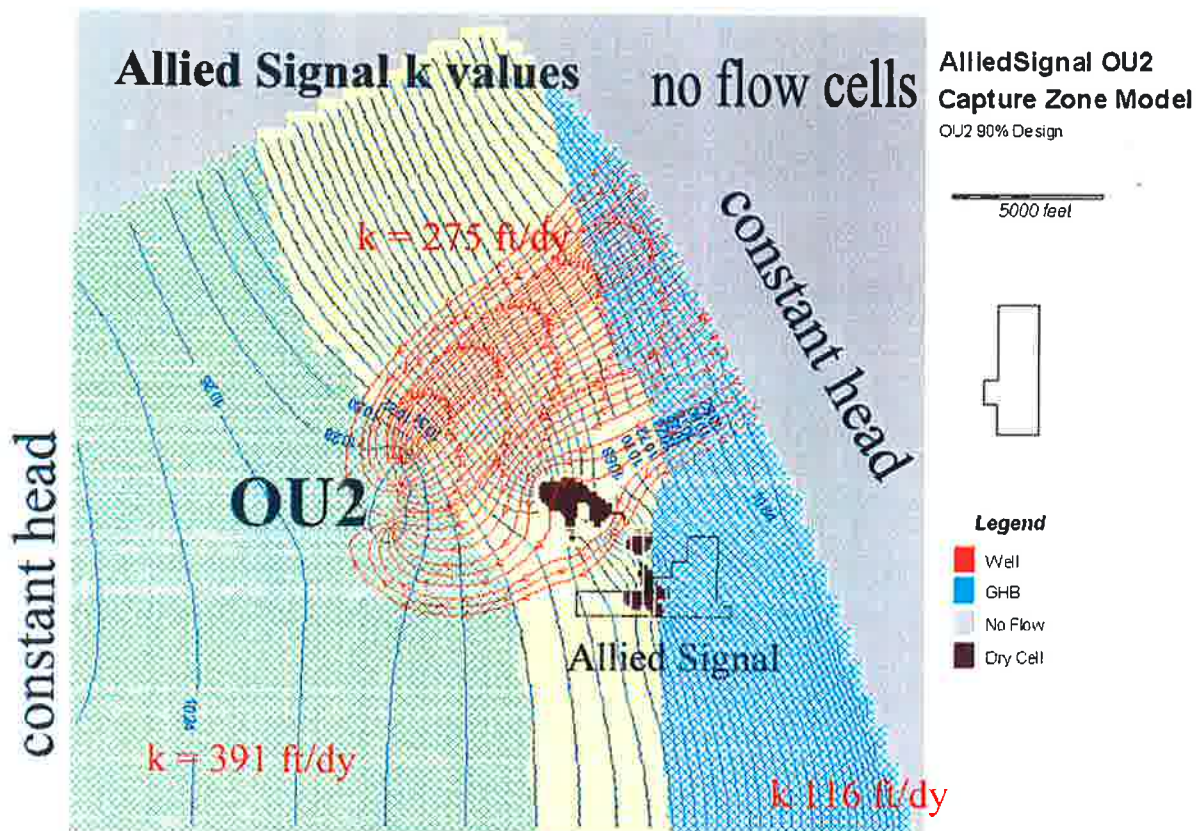
**Honeywell/Allied OU2  
model area**

**no flow**

**Motorola 1996 grid**

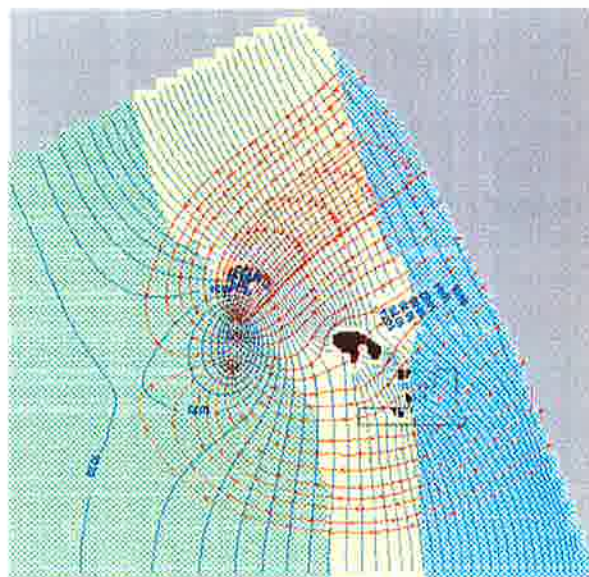
**Figure 4.1 Comparison of model domains and rotation**





**Figure 4.2 Comparison of capture zones**





AlliedSignal OU2  
Capture Zone Model  
OU2 90% Design

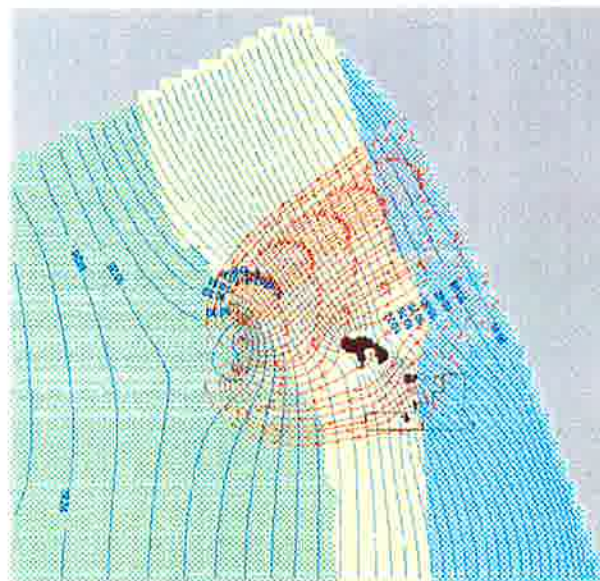
5000 feet



$k = 100$  ft/dy

**Legend**

- Well
- GHB
- No Flow
- Dry Cell



AlliedSignal OU2  
Capture Zone Model  
OU2 80% Design

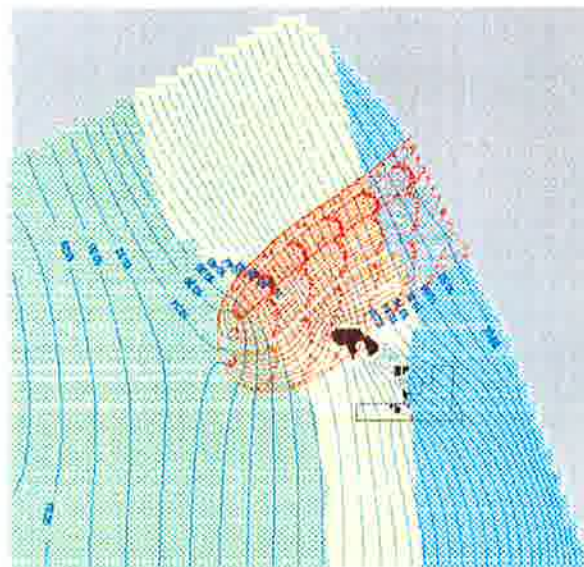
5000 feet



$k = 200$  ft/dy

**Legend**

- Well
- GHB
- No Flow
- Dry Cell



AlliedSignal OU2  
Capture Zone Model  
OU2 00% Design

5000 feet



$k = 400$  ft/dy

**Legend**

- Well
- GHB
- No Flow
- Dry Cell

**Figure 4.3 Comparison of capture zones with different but uniform  $k$  values**

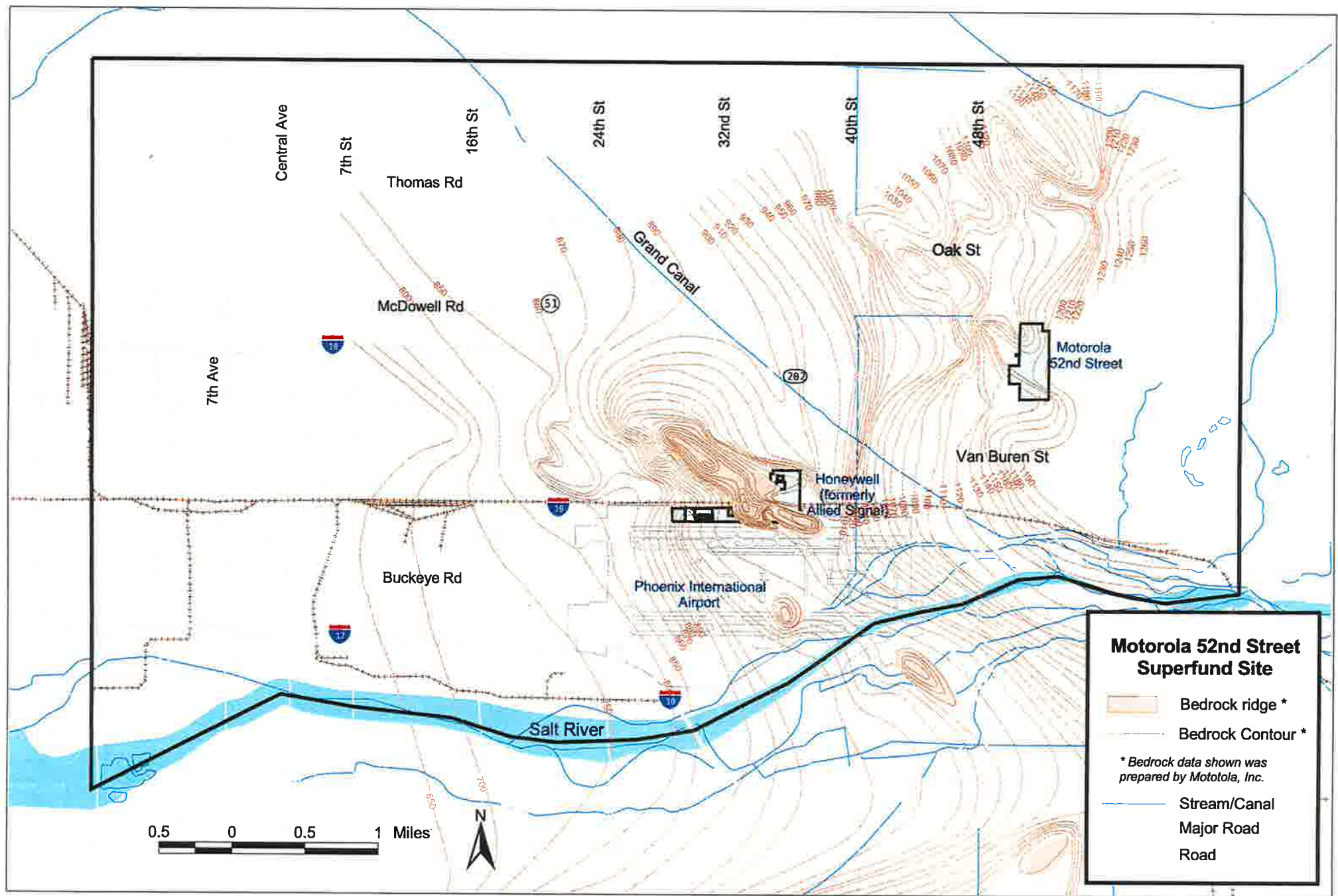


Figure 5.1 Motorola Bedrock Elevation Map



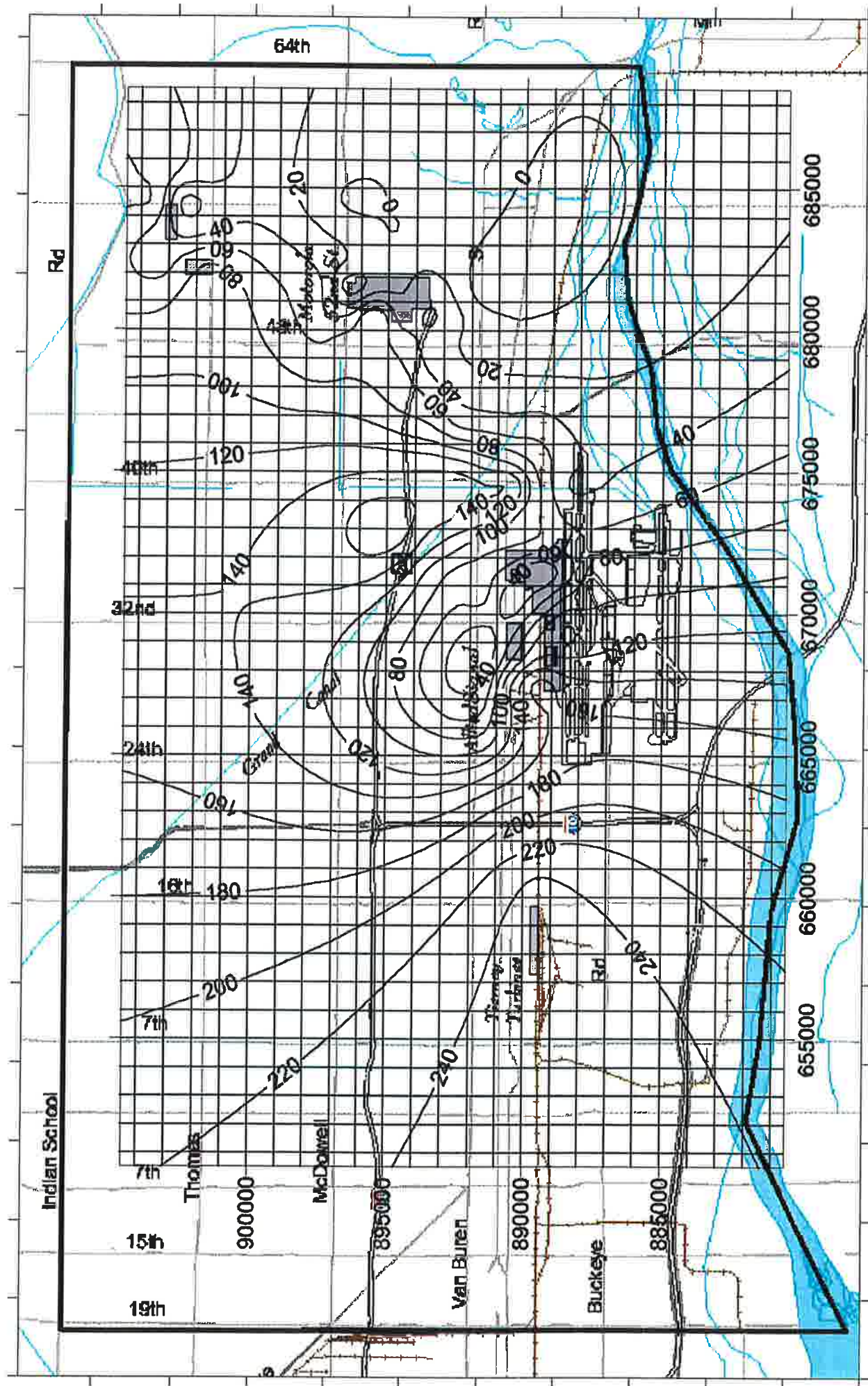


Figure 5.2

Model Grid over Aquifer Thickness



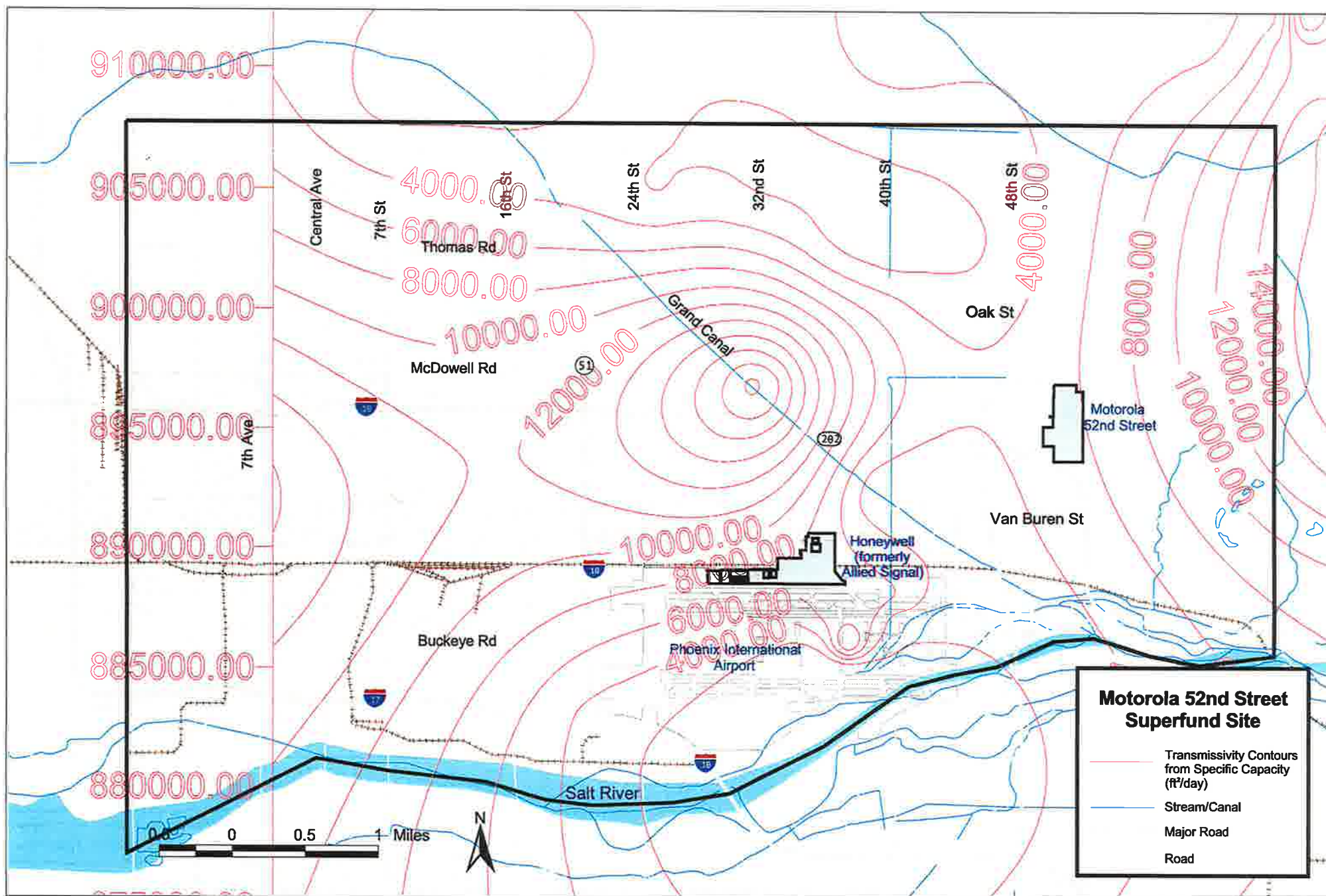


Figure 5.3 Aquifer Transmissivity from Specific Capacity

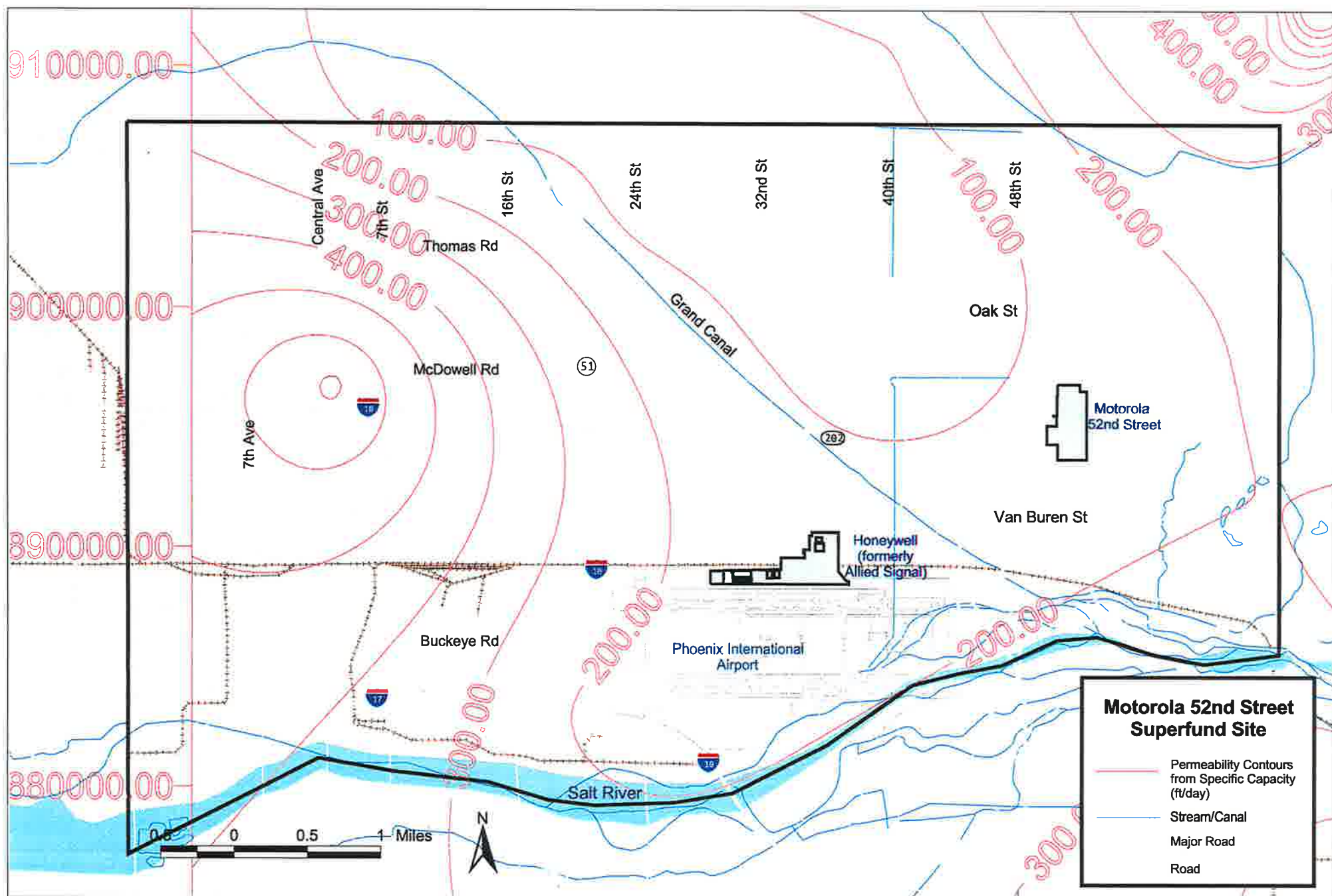


Figure 5.4 Hydraulic Conductivity Contours from Specific Capacity



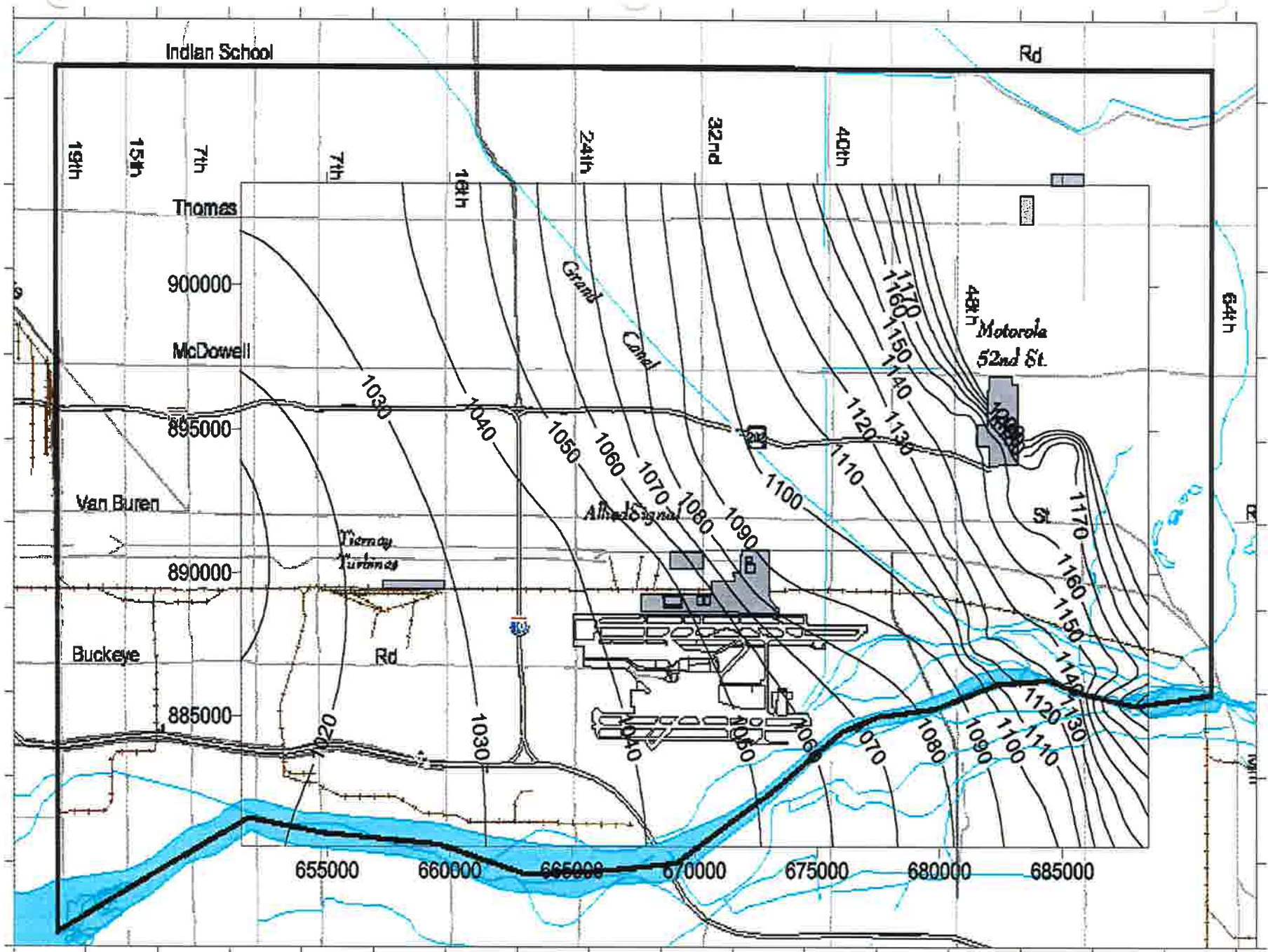
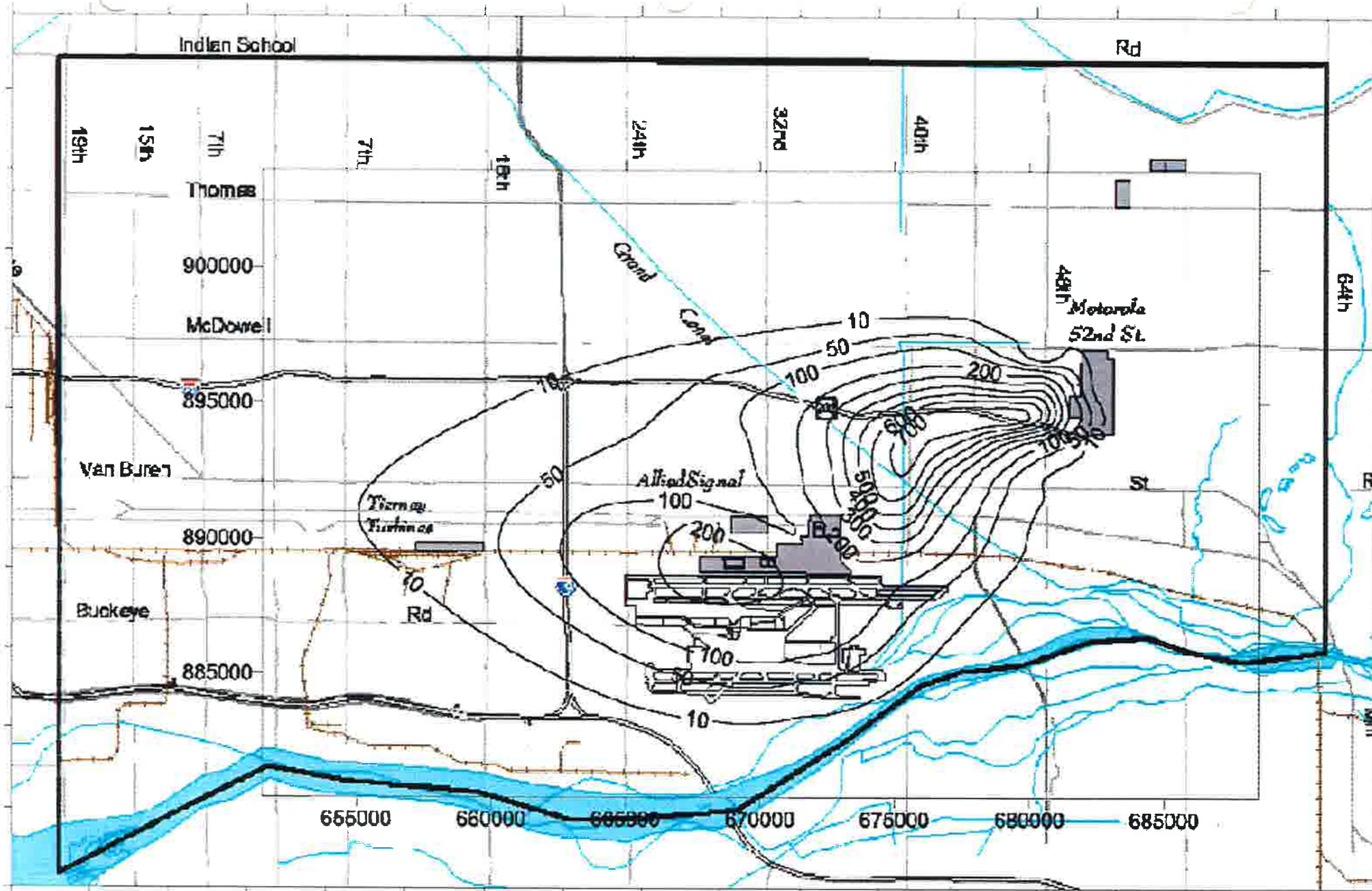


Figure 6.1 Model Generated 1996 Water Table -- Ridge Permeable



**Figure 6.2**

**Model Generated Motorola TCE Plume—ridge permeable**



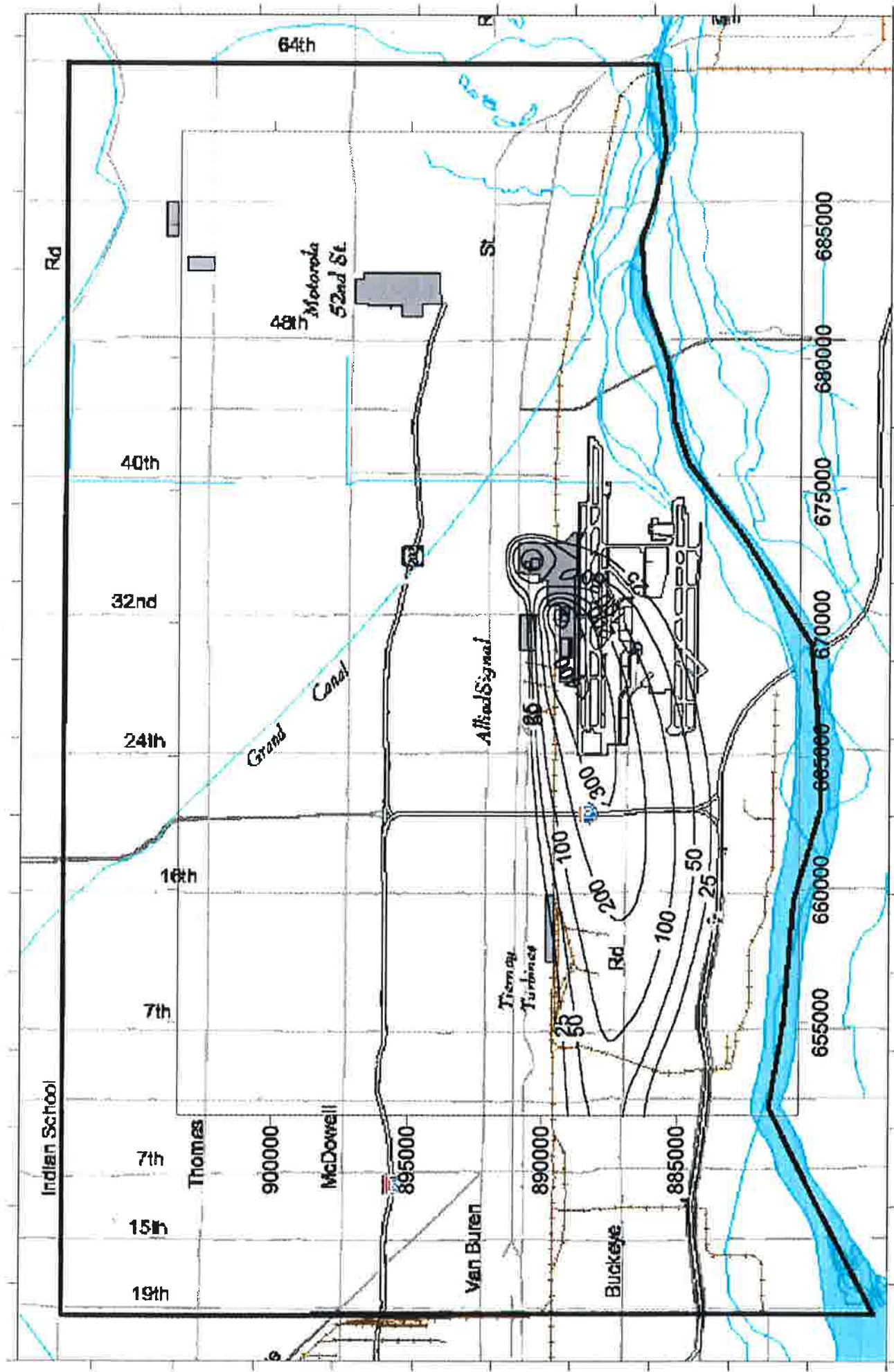
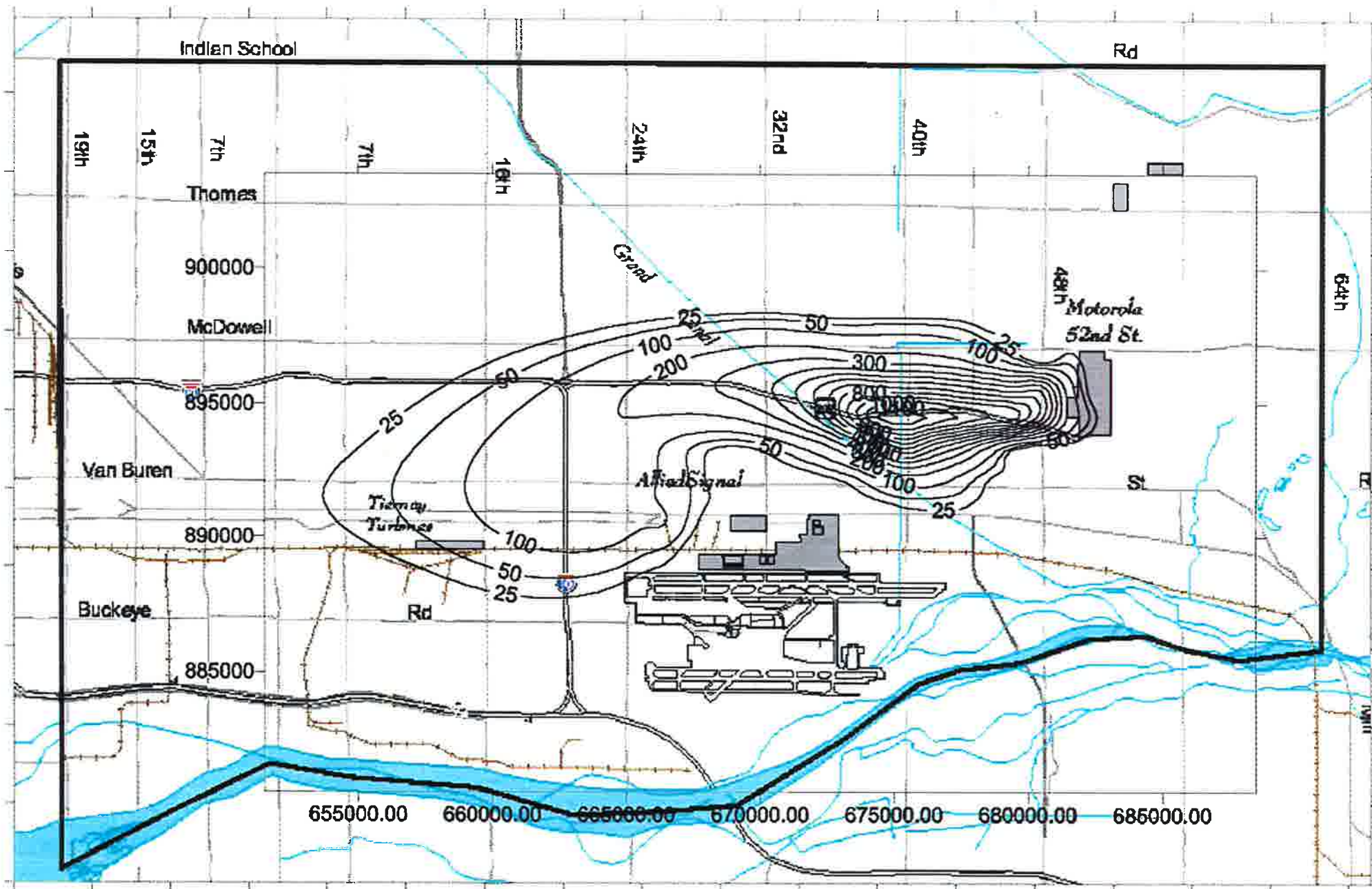


Figure 6.3

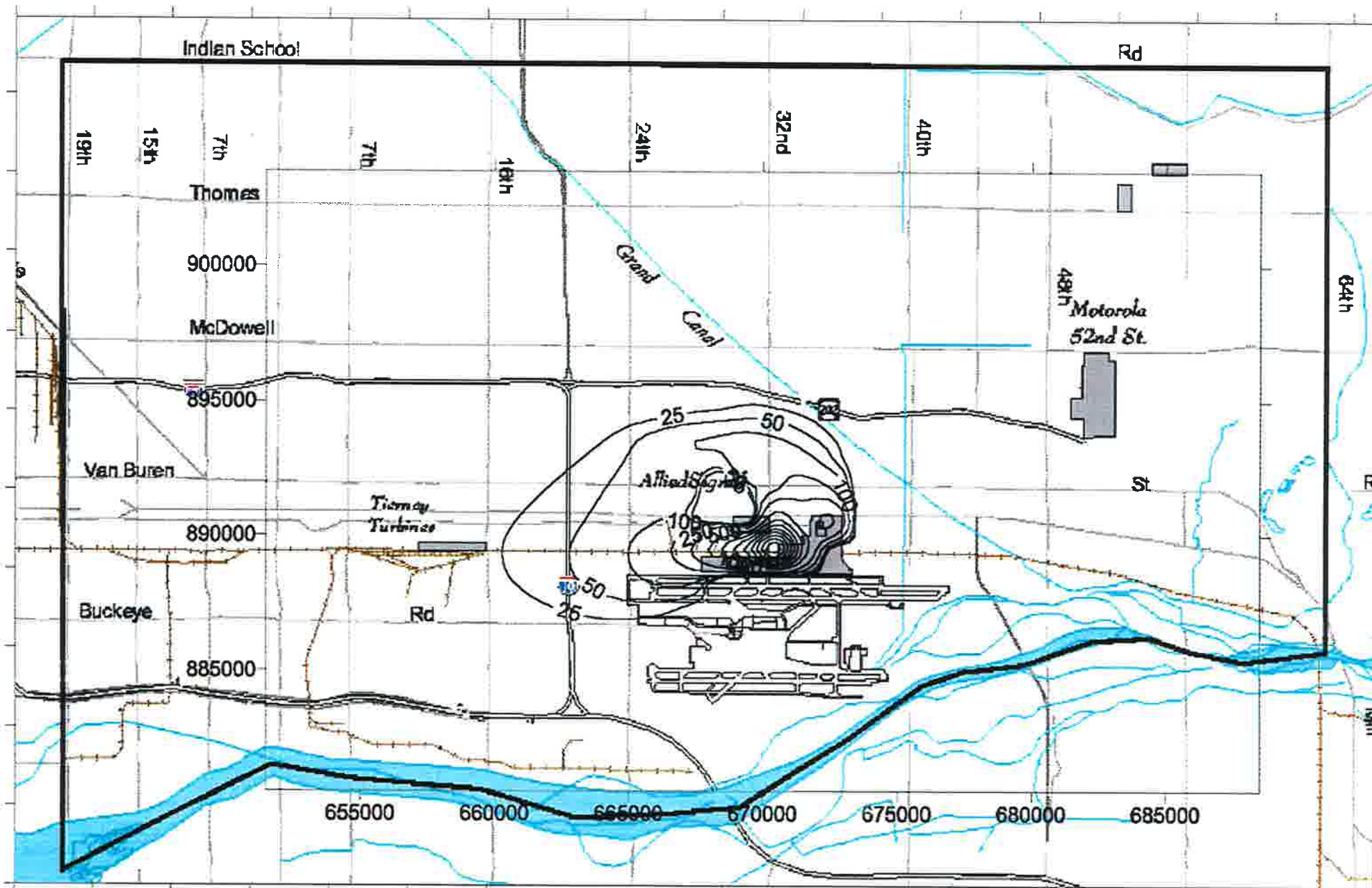
Model Generated Allied TCE Plume—ridge permeable



**Figure 6.4**

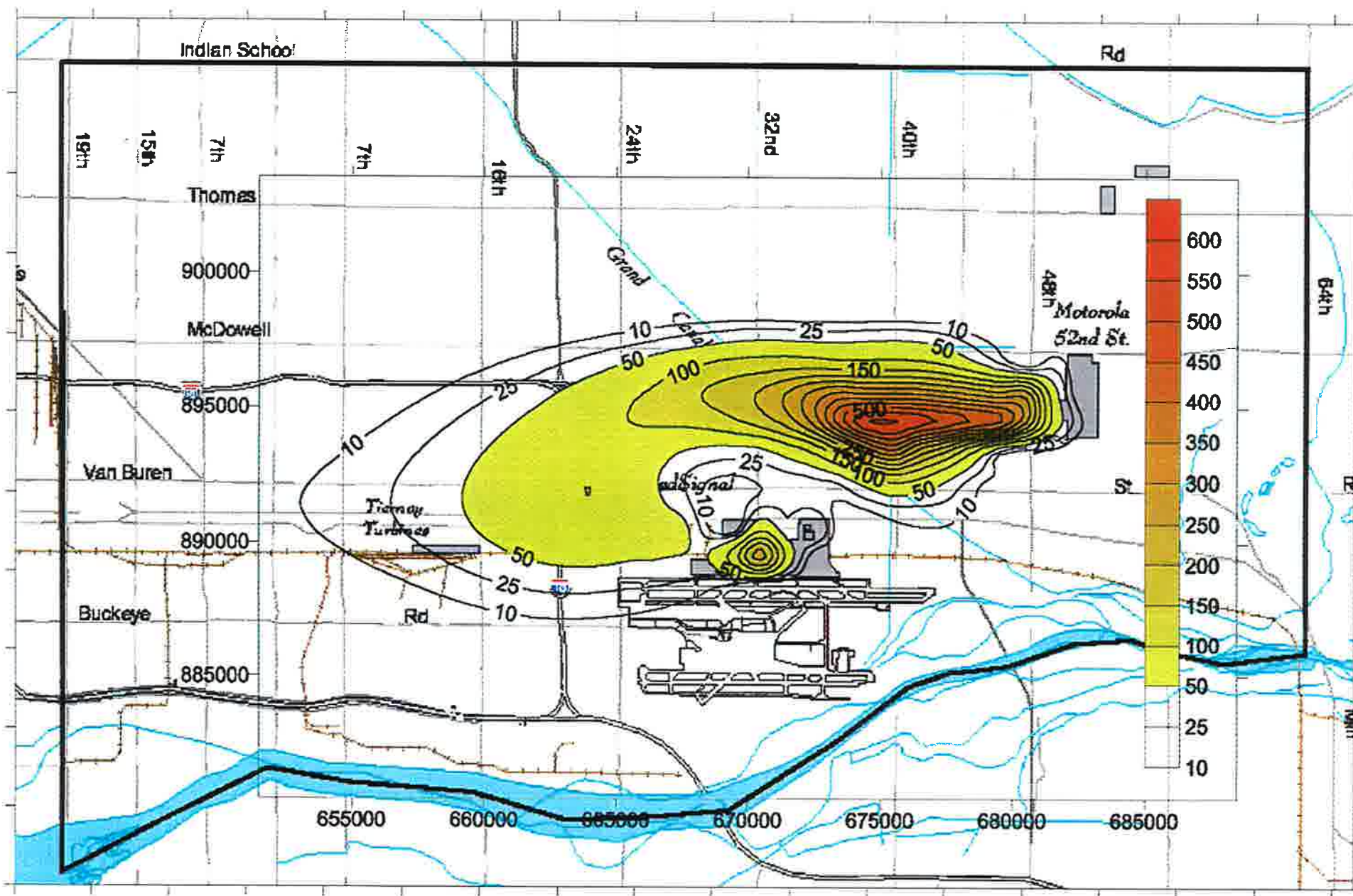
**Model Generated Motorola TCE Plume--ridge impermeable**





**Figure 6.5**

**Model Generated Allied TCE Plume--ridge Impermeable**



**Figure 6.6** Model Generated Motorola & Allied TCE Plume—ridge impermeable



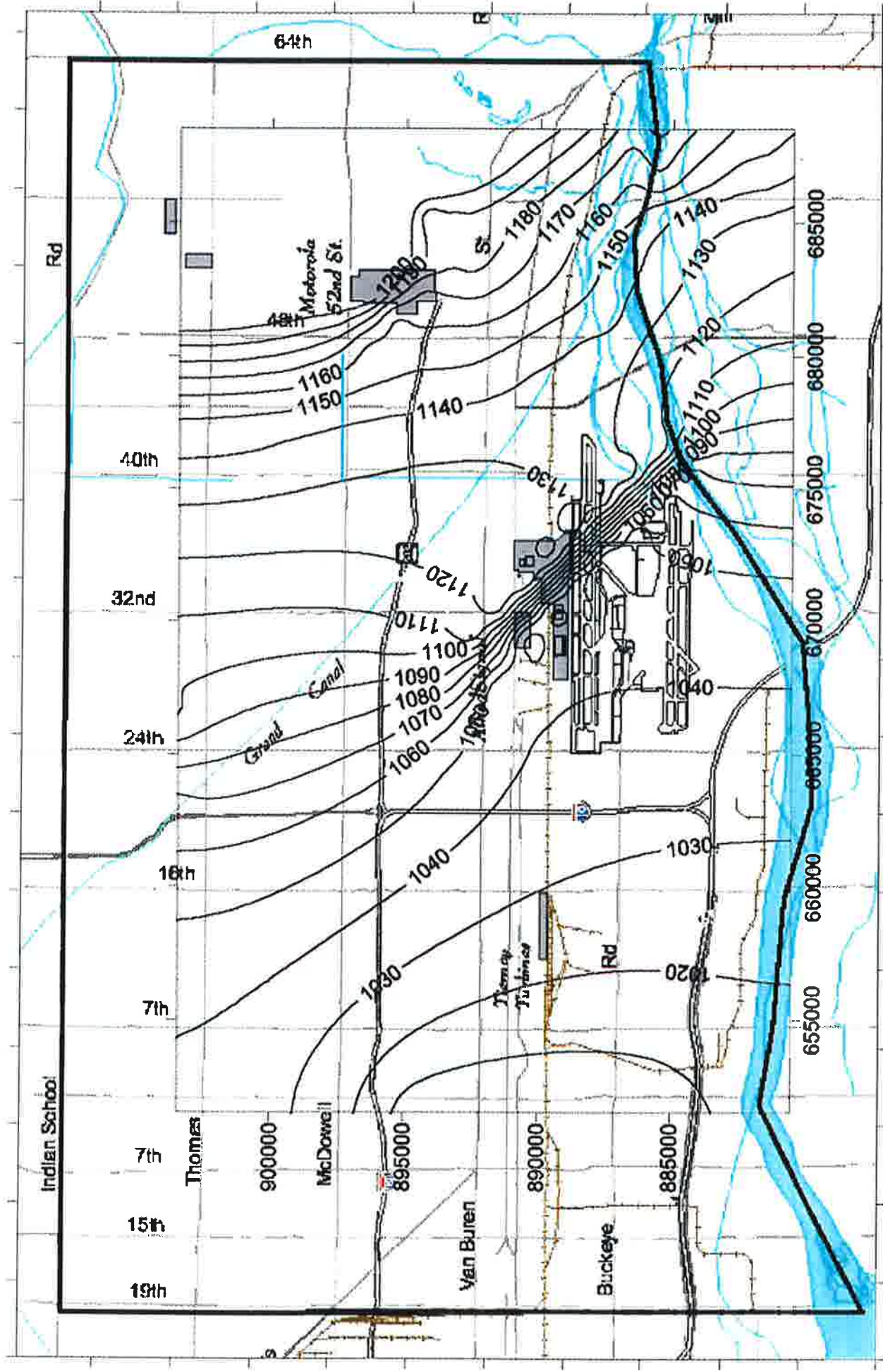


Figure 6.7

Model Generated '96 Water Table--ridge impermeable

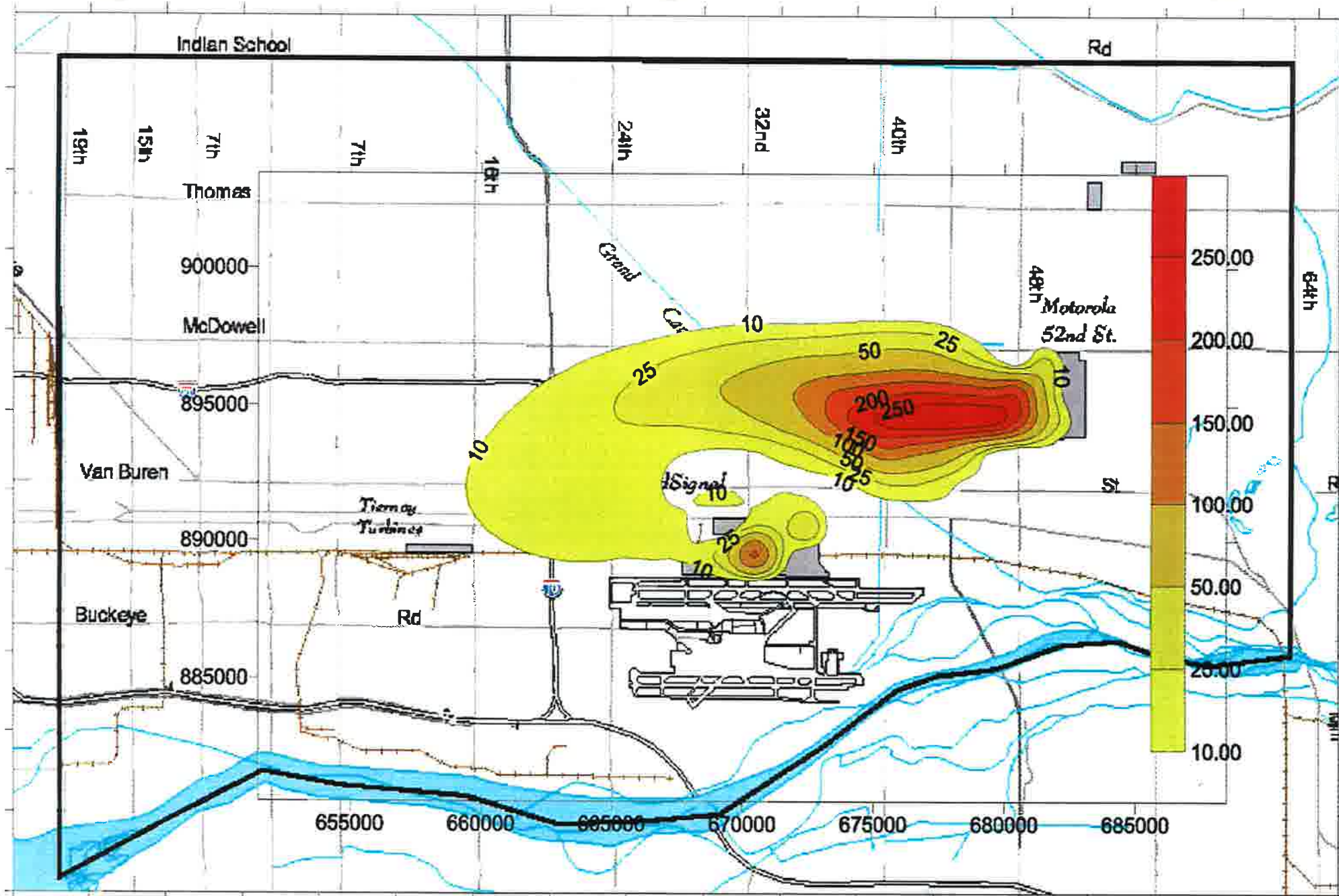


Figure 7.1

40 year TCE Plume—10 year half-life



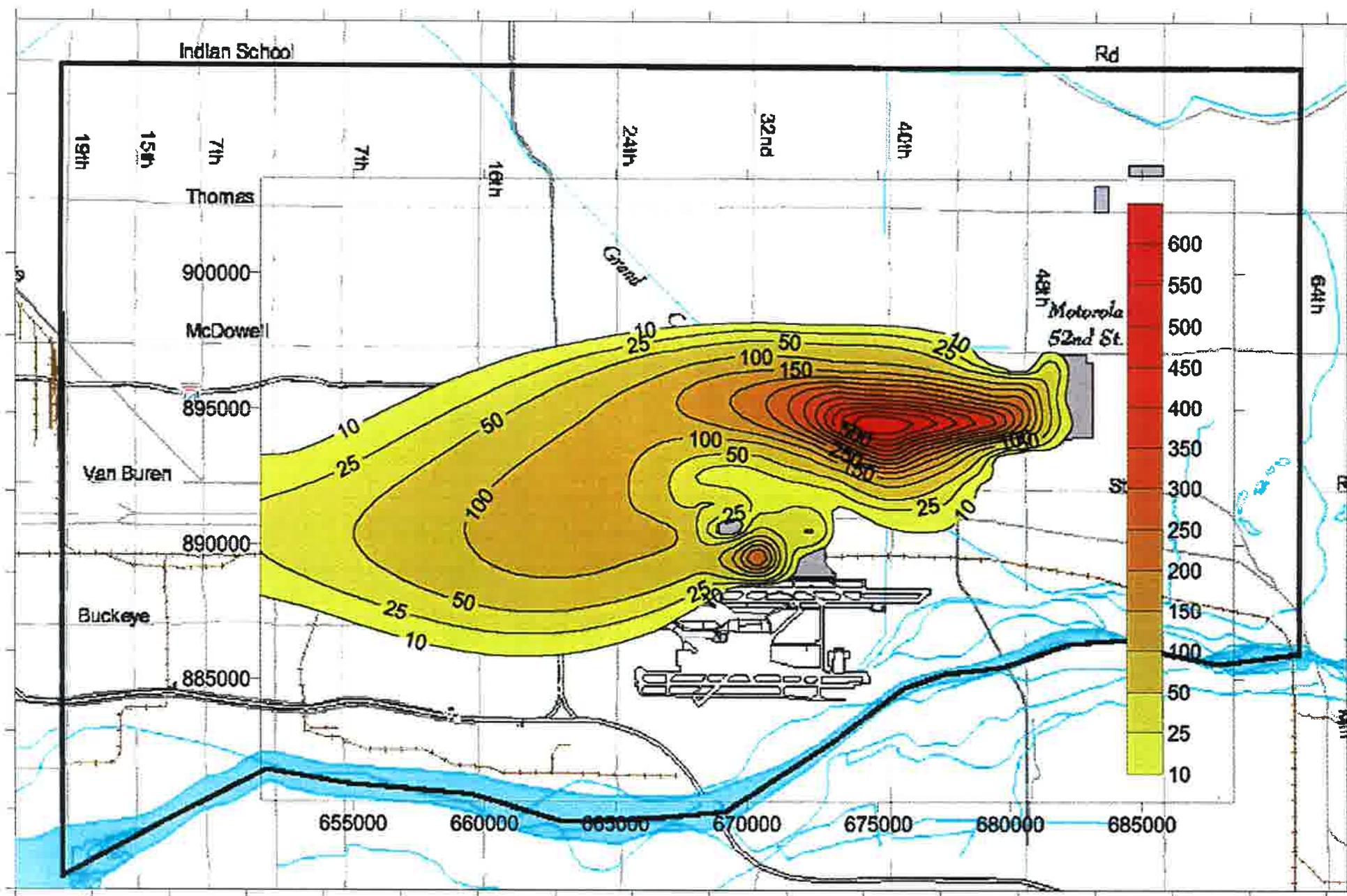
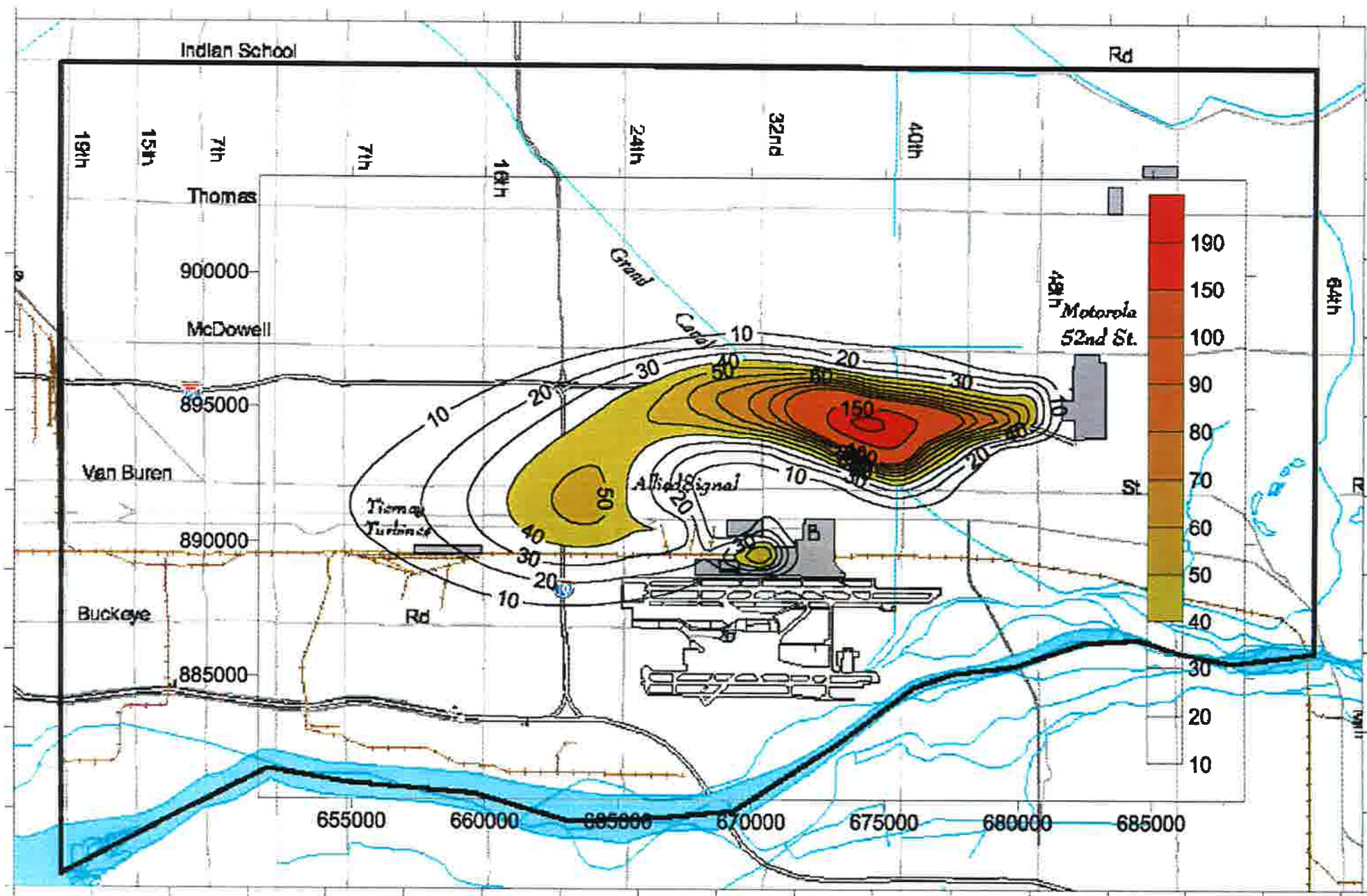


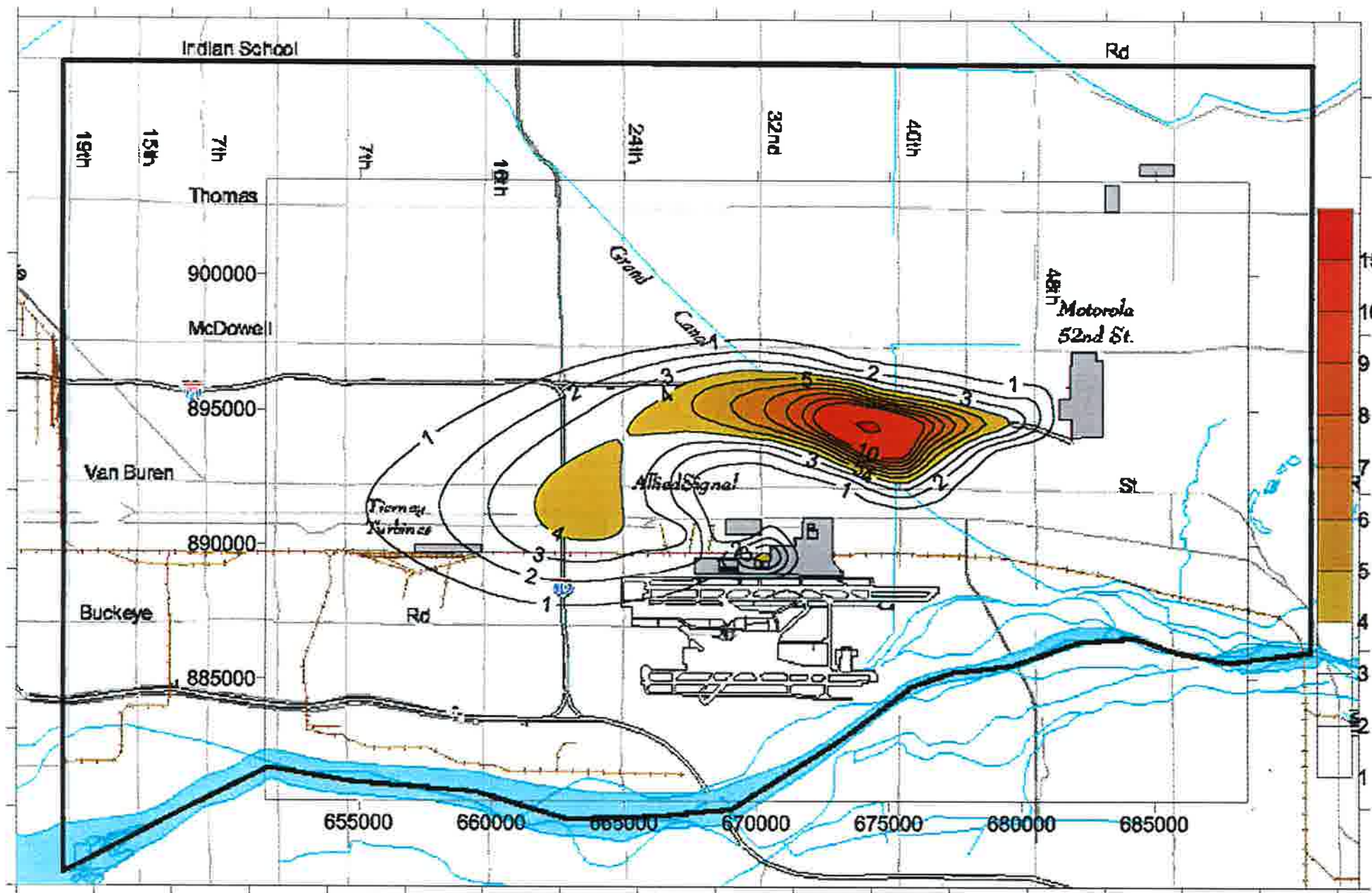
Figure 7.2

TCE—40 year half-life, 20% porosity



**Figure 7.3** Model Generated Motorola & Allied 1,2 DCE Plume—ridge impermeable





**Figure 7.4** Model Generated Motorola & Allied Vinyl Chloride Plume--ridge impermeable

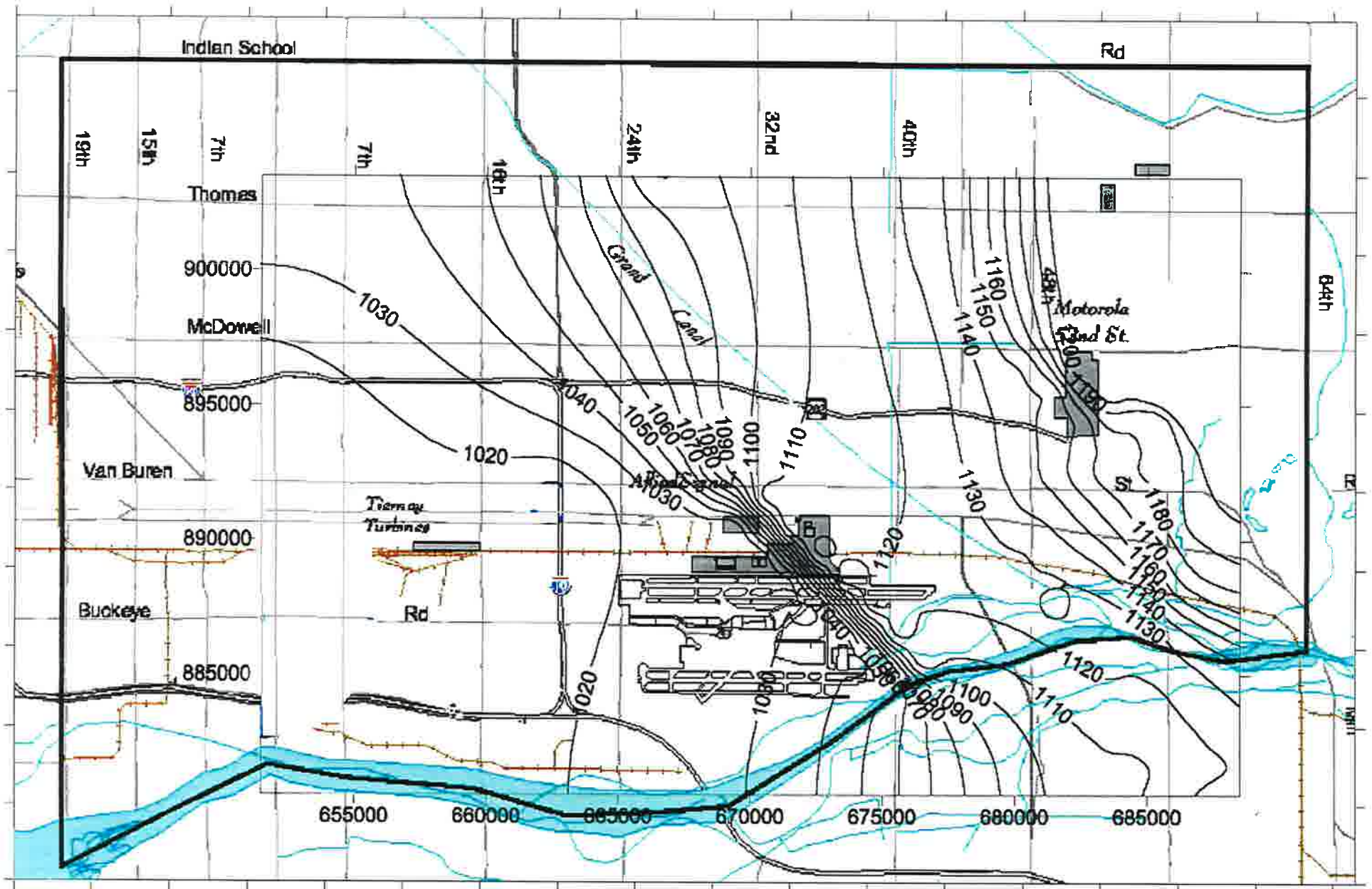


Figure 7.5

OU2--Steady-State Water Table



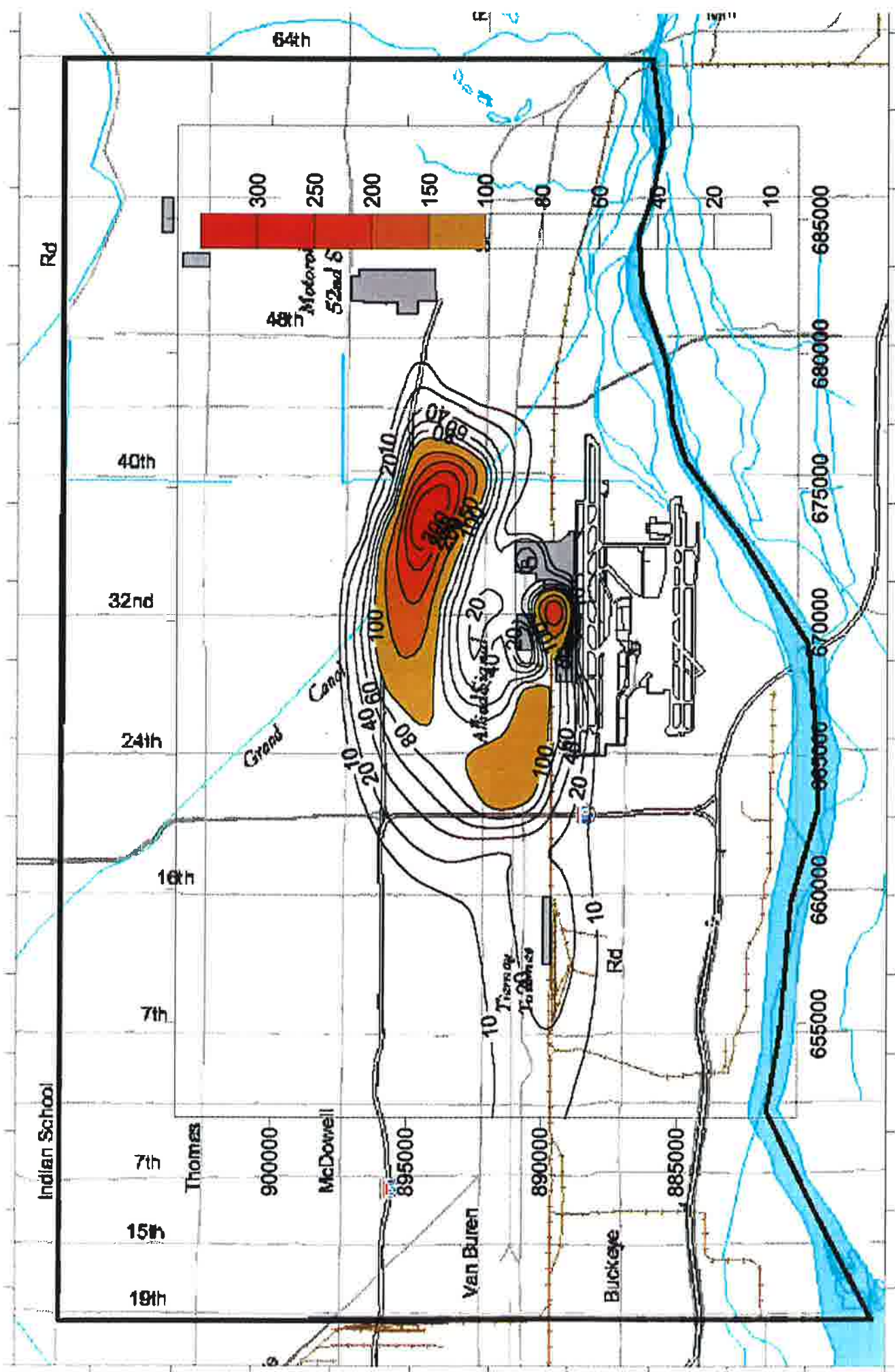
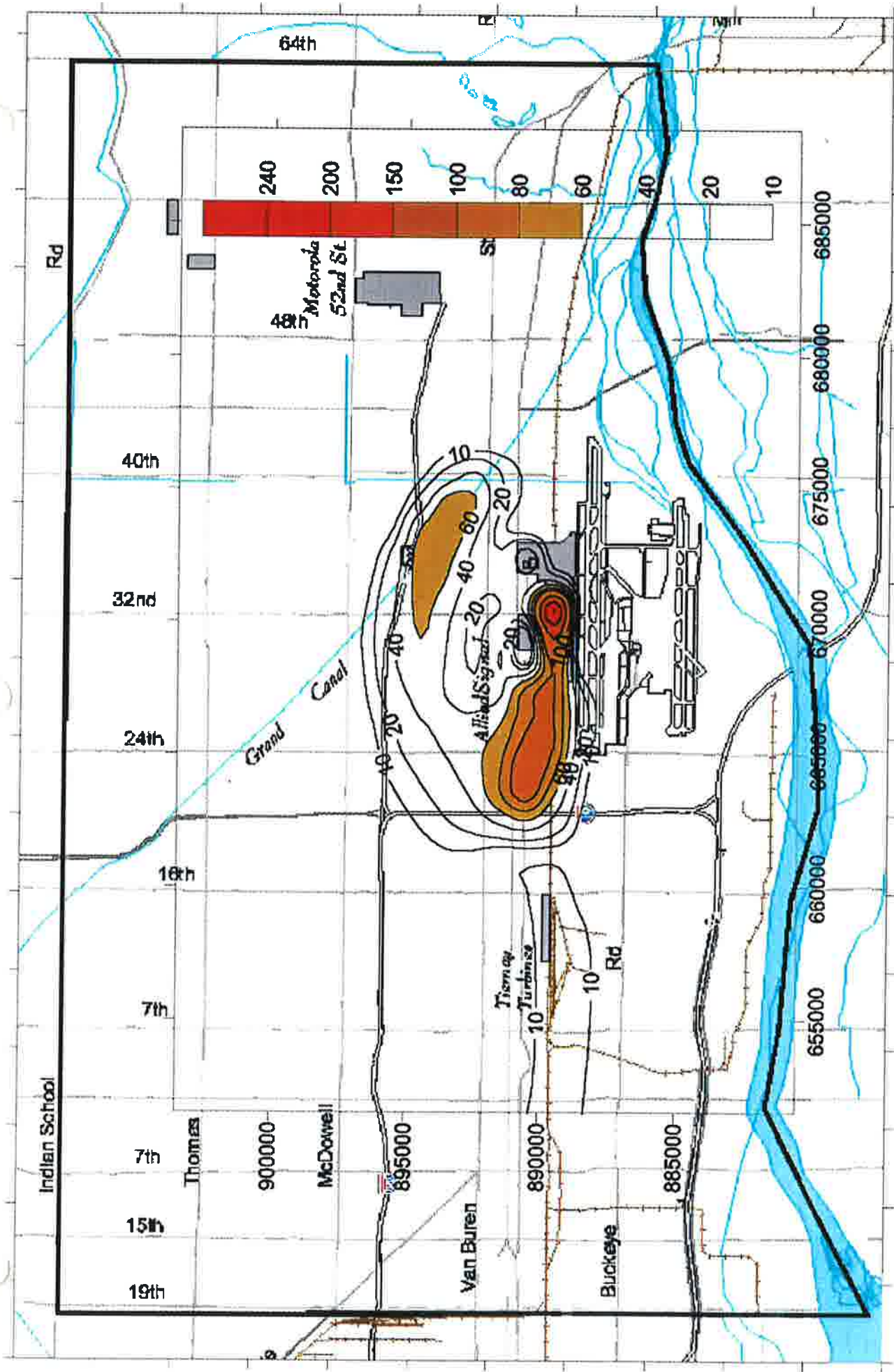


Figure 7.6

OU2-10 Years of Operations



**Figure 7.7**

**OU2--20 Years of Operations**



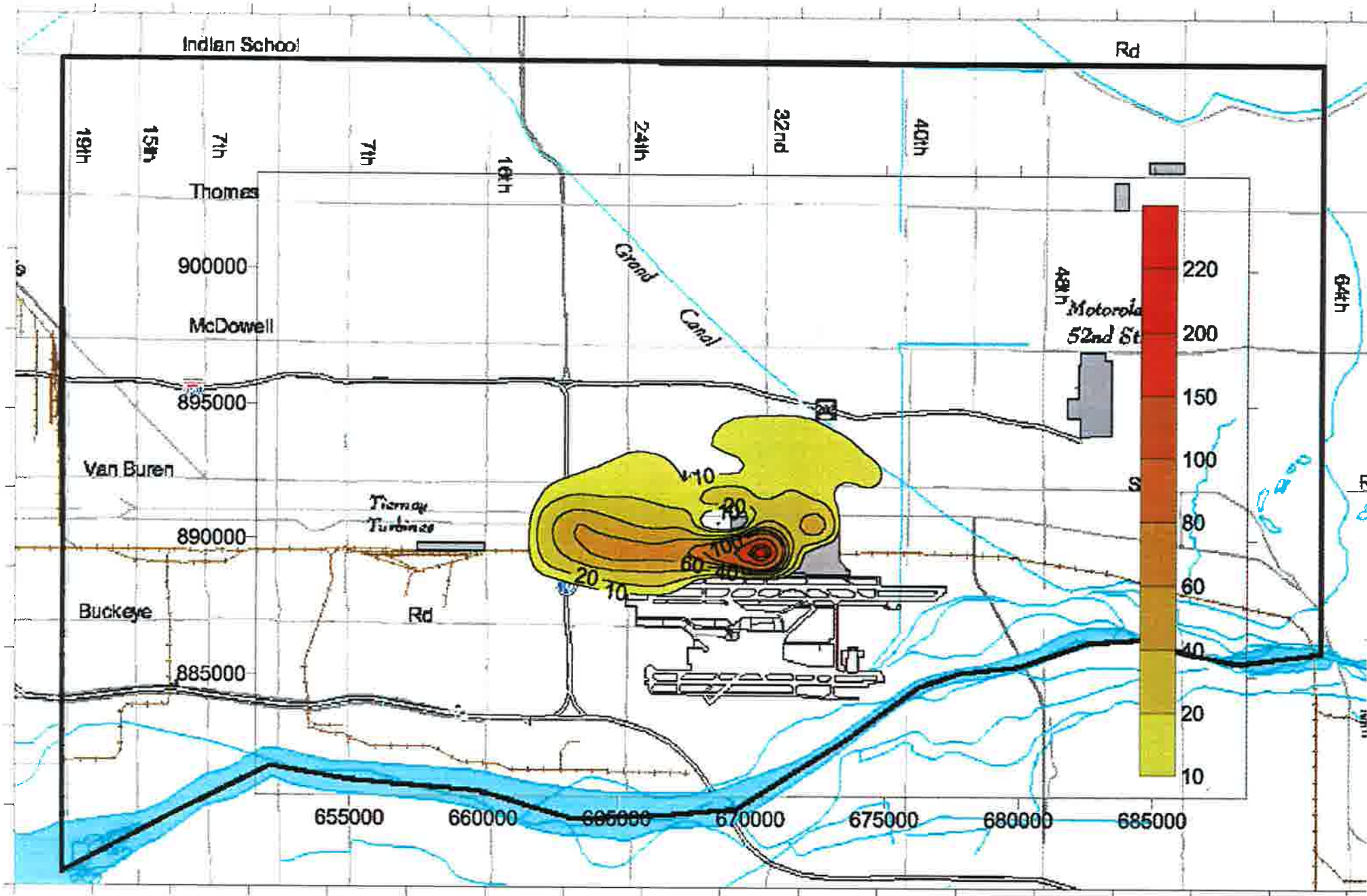
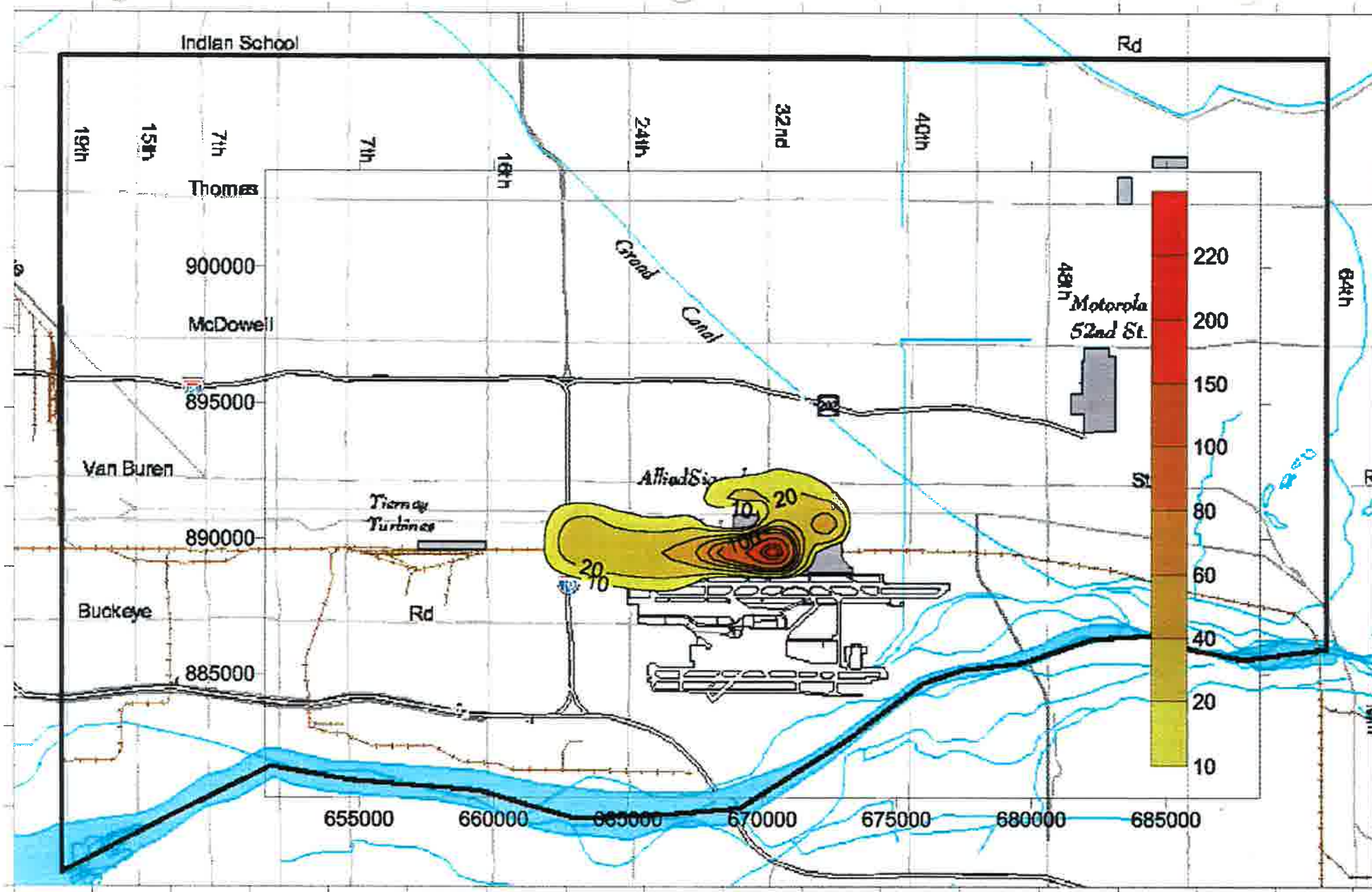


Figure 7.8

OU2--30 Years of Operations



**Figure 7.9**

**OU2--40 Years of Operations**